Renewable and Sustainable Energy Reviews 40 (2014) 1168–1191

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Building sustainable energy systems: Homeostatic control of grid-connected microgrids, as a means to reconcile power supply and energy demand response management

Franco Fernando Yanine [a,*], Federico I. Caballero [b], Enzo E. Sauma [b], Felisa M. Córdova [c]

[a] Departamento de Industrias, Universidad Técnica Federico Santa María (UTFSM); Avenida Santa María 6400, Vitacura, Santiago, Chile
[b] Department of Industrial & Systems Engineering, Pontificia Universidad Católica de Chile (PUC), Campus San Joaquin, Avenida Vicuña Mackenna 4860, Comuna de Macul, Santiago, Chile
[c] Department of Industrial Engineering, Universidad de Santiago de Chile, USACH, Avenida Ecuador 3769, Santiago, R.M., Chile

ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
18 July 2014
Accepted 6 August 2014

Keywords:
Homeostatic control
Sustainability
Power supply
Demand response
Energy efficiency
Thriftiness
Energy buffer

ABSTRACT

The issue of worldwide over consumption and squandering of electrical energy has resulted in what one might call an energy obesity problem in terms of energy intake and its expenditure. It is indeed something that must change if modern society is to become sustainable someday. This is to be realized in conjunction with adequate government policies and innovative strategies aimed at effectively integrating non-conventional renewable energies (NCRE), with thriftiness and energy efficiency (EE) – the three pillars of energy sustainability (ES) – in today's electric power systems generation and distribution infrastructure. This ought to be done in a way that incorporates them jointly, as part of a comprehensive energy strategy to propitiate a wider penetration of distributed generation (DG) solutions. Departing from mainstream literature on the subject, this paper proposes such strategies for integrating hybrid micro-generation power systems to the grid through homeostatic control (HC), as a means to reconcile power supply and energy demand response management (EDRM). These strategies can be designed and implemented in the microgrid's supervisory control system for the purpose of eliciting EE and thriftiness in consumers to build ES in the system. The theoretical model behind the HC strategies is presented and a numerical example is provided, using real electricity consumption data of a small rural community in Chile. Upon examining a particular set of criteria designed to control renewable power (RP) supply from a grid-tie microgrid to residential consumers, simulation results show that the model proves effective when testing such criteria for different power supply scenarios. Particularly revealing is the role of the energy storage system (ESS) – the energy buffer – in the HC strategies being proposed and the difference that it makes in eliciting thrifty, efficient energy consumption as a result of individual and collective efforts to ensure energy sustainability of the system as a whole.

Contents

* Corresponding author. Tel.: +56 2 23541256.
E-mail address: fernando.yanine@usm.cl (F.F. Yanine).

http://dx.doi.org/10.1016/j.rser.2014.08.017
1364-0321/

1. Introduction

Today's society is at a crossroads and in the middle of a transition stage in terms of technologies, fuels and electric power systems (EPS) management that somehow must echo the energy crisis that many regions of the world live today. This goes right in front of the problem of high CO_2 emissions and green house gases (GHG) and the purported effects on climate change, air pollution and health risks [1]. Particularly dire is the situation of those regions of the world which – unlike Denmark – rely heavily on fossil fuels for their energy production, especially so when most of such fuels are imported. Chile in particular is a good example of this unfortunate case, with its unbound energy expenditure which parallels its economic growth in a way that clearly illustrates this energy obesity problem. With an economic growth which is still closely tied to a strong energy consumption, Chile is a country where the incorporation of renewables and EE measures [2,3] along with thriftiness in energy usage, even though as important and necessary as this initiative is, it has not yet been able to click in government authorities, the legislature and the population at large inserting it among their substantive priorities to make the change possible. In fact experts predict a grim outlook for Chile moving towards 2020, due to the lack of enough new energy projects approved in a timely manner and also due to the length of such projects, once they are approved. In light of such a worrisome outlook, it is urgent to shift course towards the adoption of DG in a larger scale with renewable energy sources (RES) and innovative technologies [4], along with the adoption of EE and thriftiness in energy consumption, and to push for these to be considered jointly in the national energy policy making of the country [5–11]. Indeed it is important to understand that the larger and more widespread the diffusion and integration of NCRE, along with thriftiness and EE, all deemed as one complete set of measures and incentives, comprise the three pillars of ES. This is to be expected someday in new DG projects incorporated into the country's energy matrix – the current EPS generation and distribution infrastructure – if more effective energy policies are to be achieved. Such concerted effort must work hand in hand with advancements in EPS technological innovations [4] and power management, as part of a national energy program that fosters and impels both of these towards a more sustainable economic development. For such purpose one must also develop new strategies aimed at finding new ways of implementing energy regulation (ER) and EE measures that may elicit thriftiness and ES in energy consumption of the population at large. To be effective, such measures should encompass economic reward-based mechanisms to elicit and instill the desired behavioral change being sought in return for such thriftiness and energy sustainability [5–11].

Conditioning human behavior to adjust to changing living conditions and circumstances, adapting to new environments with different resources under various degrees of availability and supply is nothing new. It has been done many times before. There are various strategies to influence and condition human behavior and socio-technical systems in general to adopt behavioral changes, adapting to diverse scenarios [5–10,12–19]. An example of this are the many strategies found in the vast organizational change and management literature, where a great number of strategies for a variety scenarios are presented. These are designed, planned and implemented in various ways to elicit changes in human behavior and to make organizations become more efficient, nimble, innovative, productive or resilient. Another example of successful conditioning of human behavior was the first experiment of its kind, Biosphere 1, and later Biosphere 2 [14–19]. Biosphere 2 is an earth systems science research facility currently owned and managed by the University of Arizona, whose mission is to serve as a center for research, outreach, teaching and lifelong learning about earth, its living systems and – most importantly – the possibility to condition humans to live in controlled environments under stringent conditions [14–19]. This in order to be able to adapt to new, more complex and changing scenarios such as the ones space colonies will most likely find upon achieving planetary colonization in the decades ahead. After spending prolonged periods in these locked controlled environments where they were subjected to special living conditions, adopting strict diets with rigorous low energy (low-calorie) diet and high

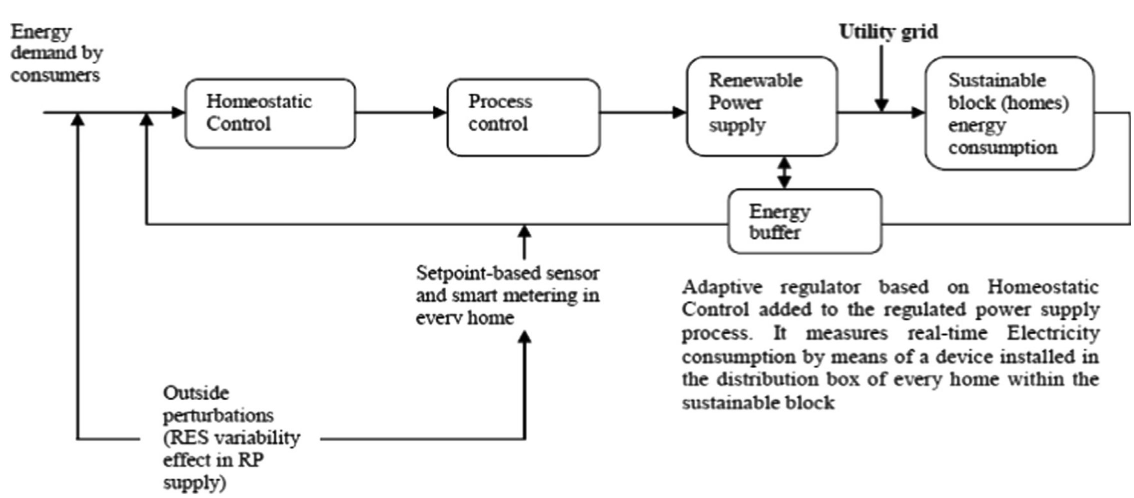

Fig. 1. A simple adaptive regulator model based on HC implemented through negative feedback for residential consumers with an energy buffer.

nutrient regimen wherein their metabolisms and homeostatic regulation (HR) processes were put to the test, they showed strikingly similar improvement in health indices as those of athletes [16–19]. Such improvements included lowered blood cholesterol, blood pressure, and significant enhancement of the immune system, turning their metabolism and overall system functions much more efficient, effective and resilient than before [14–19]. They lost an average of 16% of their pre-entry body weight before stabilizing and regaining some weight during their second year. Subsequent studies showed that the metabolism of researchers living in the biosphere became more efficient at extracting nutrients from their food as an adaptation to the low-calorie, high nutrient diet [14–19].

Unlike what has been done in other realms of science, particularly in the social and biological sciences, very little if anything has ever been proposed in regards to strategies for conditioning human behavior under changing energy supply scenarios [5–10]. Thus emerges the idea of employing HC in hybrid energy systems such as microgrids tied to the mains in order to instill behavioral changes in residential consumers to lower their energy intake. This is to be achieved by devising innovative strategies to condition renewable electric power supply to energy users based on a predefined set of criteria [5–10]. This is to be planned and implemented in a predetermined manner, obeying to the characteristics of the target community, the local climate conditions, and the site laws and regulations present which condition the technology that can be used such as smart metering and energy storage, among other factors. The approach proposed here seeks to manage consumers demand response efficiently and effectively in the context of (renewable energy technologies) RETs, supplying power to a group of residential consumers. These criteria operate by adapting/adjusting the energy consumption patterns of consumers to fluctuating power supply conditions – whether it is from the electric utility grid or from a renewable microgrid or from both – to become thriftier, more energy efficient and resilient to change. This of course is not only important for large-scale integration of NCRE and for building sustainable energy systems (SES) everywhere, but it becomes even more important and meaningful when looking at the rapid and abrupt climate change

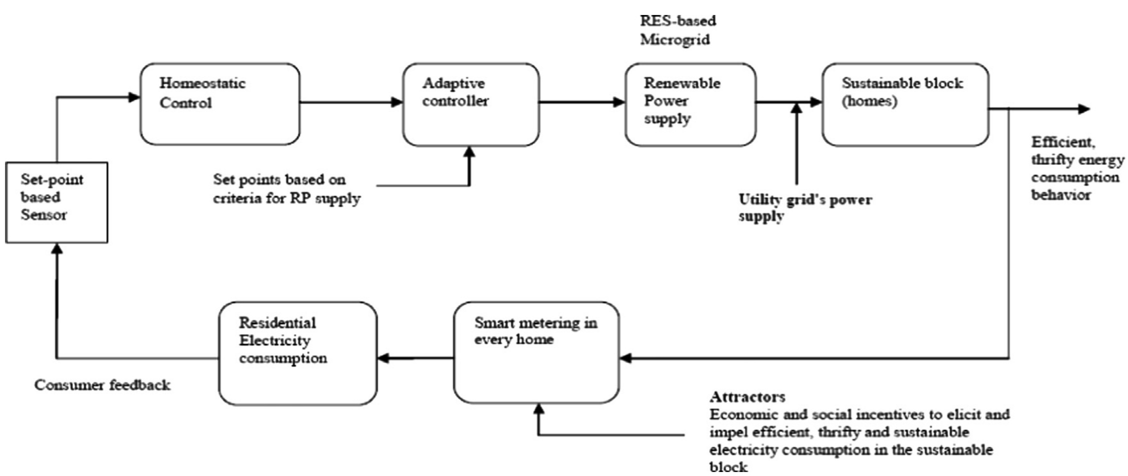

Fig. 2. Negative feedback control system diagram showing homeostatic control of a grid-connected microgrid.

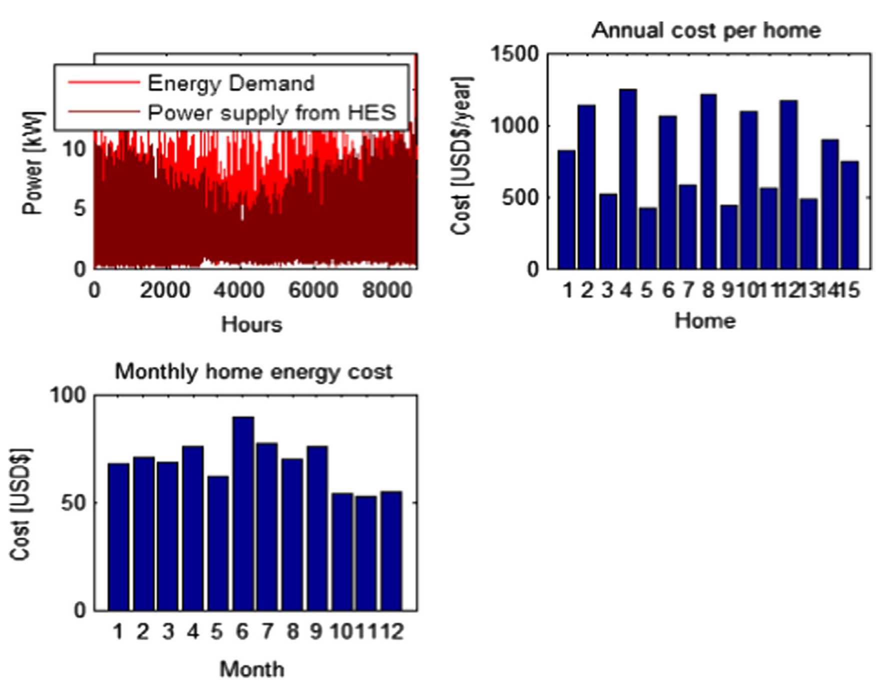

Fig. 3. Criterion 0 simulation results for the sustainable block with Potencia_HES where the hybrid energy system is operating at normal RP supply capacity.

in many parts of the world at present and where Chile is not exempt [1]. Increasingly menacing natural phenomena such as strong winds, floods, and seismic activity of important magnitude are more frequent now than before almost everywhere, especially in North America, and some regions of South America. Countries like Chile are a good example of this fragility state being exposed, where vital utility services such as water and electricity are continuously being threatened by such phenomena, and where the electric transmission and distribution service infrastructure is clearly at risk of collapsing [5,20–22]. All these changes and the risks they pose to society call for one thing quite clearly: the need for systems to adapt, particularly when it comes to sociotechnical systems like the microgrid supplying energy to consumers. Thus anywhere you look nowadays you find socio-technical systems [12,13] of various kinds, with diverse degrees of complexity, different aims and goals and management styles. Within these socio-technical systems there is an immense variety of work systems which are designed and implemented to pursue various objectives. To accomplish this, such systems are required to control different processes in a given environment on an ongoing basis, supervising them continuously. Whether this happens in industry, in organizational management or in nature, such processes usually work in a network of complex interdependencies of dynamic systems, supporting fast and continuously changing decision making processes [23]. These are conditioned by one or more controlled variables, where the systems involved are continuously monitoring changes that affect such processes, thus detecting the need to adapt to on-going strategies [5–10,23]. It is in this way that intelligent adaptive systems become resilient and capable of increasingly managing their capacity of adaptation more effectively [5–10,24,25]. Crucial to the effectiveness of such sustainability management capacity are the system's built-in capabilities which allow anticipated changes and various kinds of environmental stress on the system to be successfully handled [5–10,24,25]. Such sustainability management capacity comes from strategies designed and built into the systems themselves,

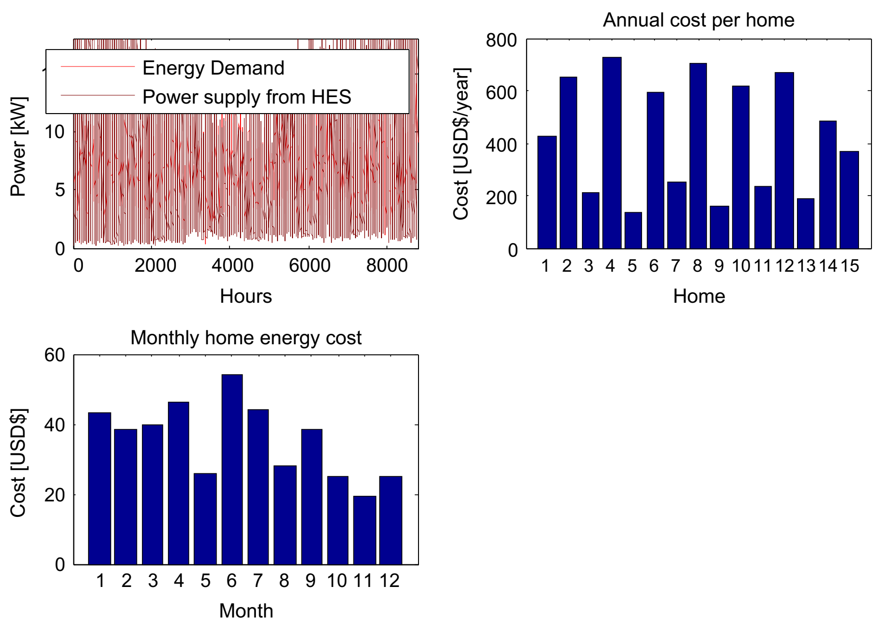

Fig. 4. The simulation results for Potencia_HES1 with double the amount of RP supply available to the block.

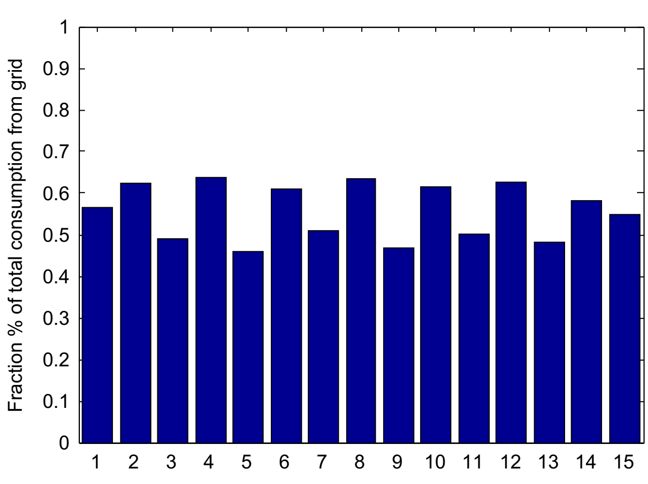

Fig. 5. Grid_frac with HES operating at normal RP supply capacity. The rest must come from the Grid or the energy buffer or both.

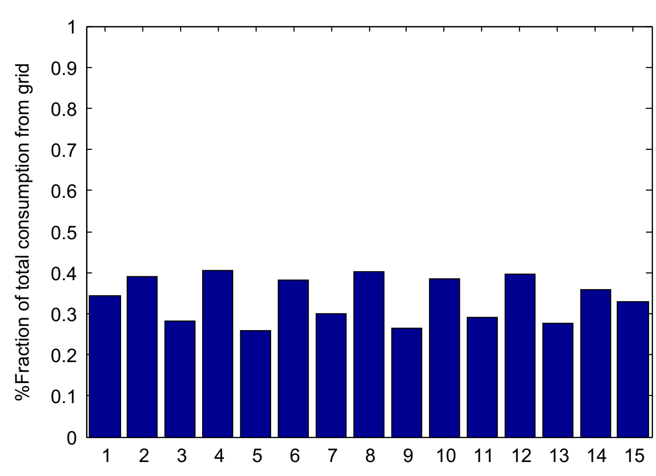

Fig. 6. Grid fraction function (energy drawn from the Grid per each of 15 homes) for Criterion 0 with Potencia_HES1.

where reinforcement learning [19] and conditioning mechanisms operate as enablers of homeostatic regulation (HR) and adaptation in such systems to obtain the desired system response. Along this line of thought an interesting attempt at implementing human conditioning in the context of this paper is presented in [26] where the smart microgrid concept in a remote location is addressed. Here the microgrid is the key enabling technology for renewable energy development, and EE improvements [26]. For the authors the smart grid represents a vision for a digital optimization of electric power transmission and distribution grids as applied to current operations, enhancing the grid security and opening up new ways of tapping alternative energy sources [26]. In the implementation of a very small grid-connected renewable microgrid, they propose Internet Protocol (IP) on home devices for data monitoring and transmission, thus making it possible for the smart microgrid to send information back and forth between the distributed electric utility grid and the customers. Along the same line of work, authors in [27] propose an energy EDRM strategy for a system with a significant intermittent generation, e.g. a microgrid employing only RES. In this system, consumer demand can shift to reduce peak power demand and also peak shaving in order to mitigate the system's power fluctuations; however this action requires evaluating the value of lost load for consumers. Emphasis is put on the need for reliable, real-time control and monitoring systems when a high penetration of DG is present. For the microgrid, the main goals of the energy management system are to deliver active and reactive power generation set-points for the generation sources, including the battery bank used in this particular case, and to send signals to consumers eliciting behavioral changes in energy consumption. Along a similar line, Palma-Behnke et al. [26,27] talk about an electricity generation system based on diesel-fueled generator to be intervened by a technological transformation, meaning that a more sustainable energy system is to bring changes and challenges to the community as compared to the original conditions, thus requiring resilience on the people's part, and the need to adapt to these changes [21–23]. The methodology referred to in the paper corresponds to the assessment and intervention stages of the project, developed between November 2009 and February 2011 in Huatacondo, a tiny village of approximately 100 inhabitants in a remote northern mountainous region of Chile. As a relevant observation one can say that the system proposed in [26,27] seems like a good idea to address EDRM in a microgrid power generation scheme, and thus it seems suitable to use a large display giving the state of the system and the RES availability. Yet for larger communities, in the several hundreds or thousands of people this approach, which is clearly tailored for a very small village, is unsuitable.

In light of the above, this paper aims to revisit the concept of HC of EPS introduced over 30 years ago, but this time focusing not on utilities but on micro-generation power systems, especially those operating connected to the distribution grid [28–53]. Many of these employ supervisory control systems similar to SCADA to coordinate and control the microgrid's power supply, in the case of this paper, to a group of residential consumers somewhere termed a sustainable block [6–11]. The paper starts with the introduction of the subject matter, briefly discussing homeostasis and HR in living organisms and how these concepts may also apply to EPS; particularly to smart microgrids tied to the grid, operating with energy storage [52,53] whenever it is appropriate and possible to do so. Thus the paper aims to bridge concepts from biology and medicine to the management and control of electric power supply, energy demand and consumption (loads) and how these can be reconciled and adequately matched through HR principles emulating what happens in nature. Section 2 presents the highlights of HC and describes briefly the basic philosophy and principles behind it, along with recent work by other authors. This section also presents the theoretical HC model for grid-connected microgrids where the general characteristics of this new technology are discussed. Efforts are made to focus particularly on one specific set of attributes as key elements of the model proposed. Section 3 presents the general approach and methodology where HC strategies are introduced based on RP supply control criteria for smart microgrids. This is aimed at building SES, where the need to arrive at and maintain system equilibrium is paramount. Finally Section 4 presents the findings and the analysis of the simulation results. Particularly relevant to the model proposed is the interaction between the sustainable block coupled to the grid-connected microgrid and the electric power grid (the mains) under the different RP supply control criteria being tested. It is not only revealing but also counterintuitive to find that results are even better when there is energy storage [52,53] present in the system as opposed to operating without energy storage, making a clear distinction between the two. The paper concludes with a general discussion of the findings and how these tie to the core of the subject matter of this paper, highlighting major results as well as the outlook envisaged for future work in the field.

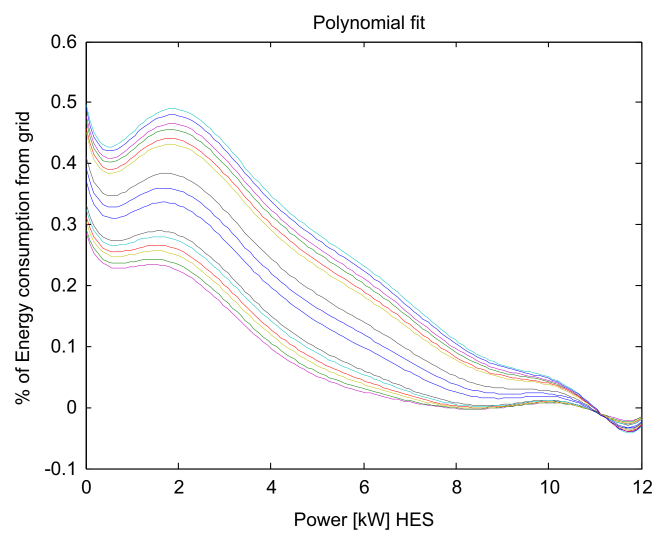

Fig. 7. Polyfit function showing the relationship between the electricity consumption of the sustainable block from the grid and the power supply available from the HES.

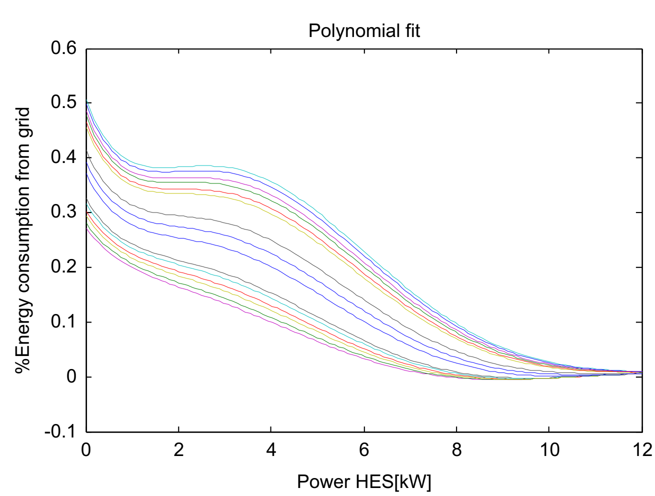

Fig. 8. Polynomial fitting function for Criterion 0 with Potencia_HES1 (double the amount).

2. Homeostasis and homeostatic control (HC) of electric power systems

2.1. General discussion

Homeostasis is an important concept which is rooted in biology and medicine as it is present in living organisms everywhere, and one upon which HC is inspired [54–80]. It is a biological term referring to the existence of a state of equilibrium or the process towards such equilibrium; namely it is "*a relatively stable state of equilibrium or a tendency toward such a state between the different but interdependent elements or groups of elements of an organism or group*" [55]. Homeostasis is that condition in which the internal environment of the living organism or group of organisms remains relatively constant yet making the necessary adjustments to maintain its operation and its system's functions in place – towards efficient equilibrium – despite changes in the external environment. This is so to maintain a state of balance, adjusting

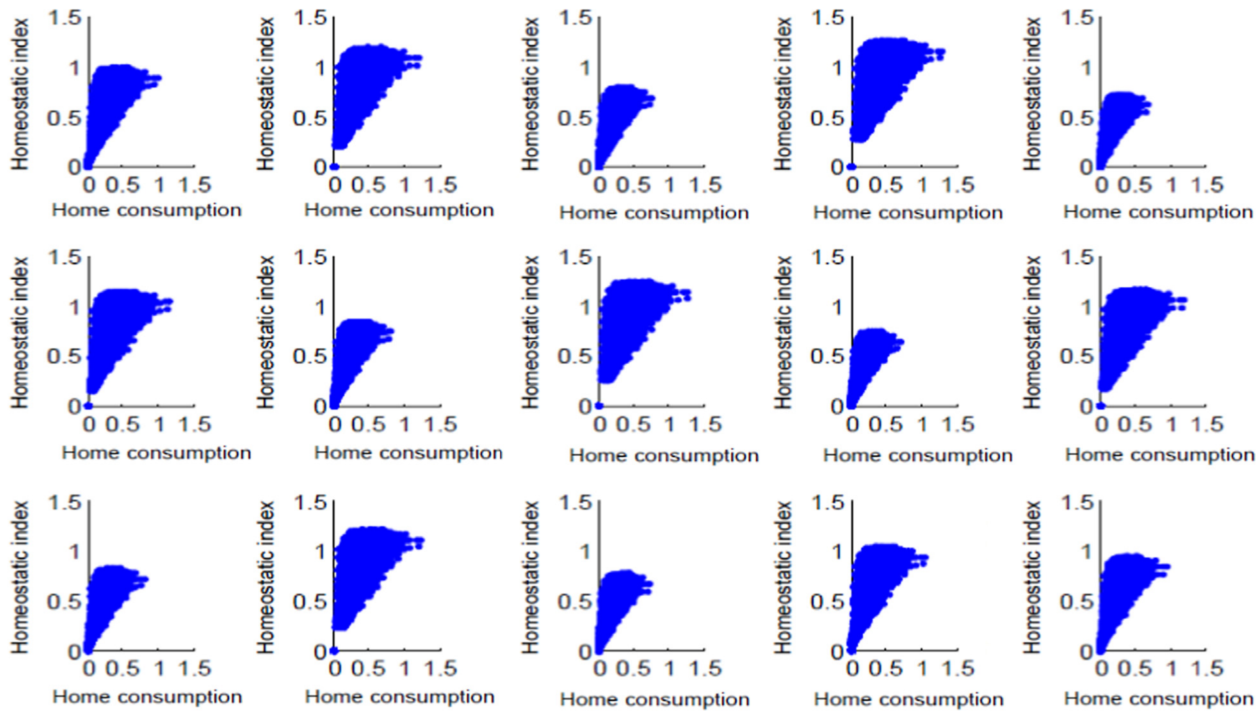

Fig. 9. In this illustration H_i function is shown for the HES with energy storage and Potencia_HES.

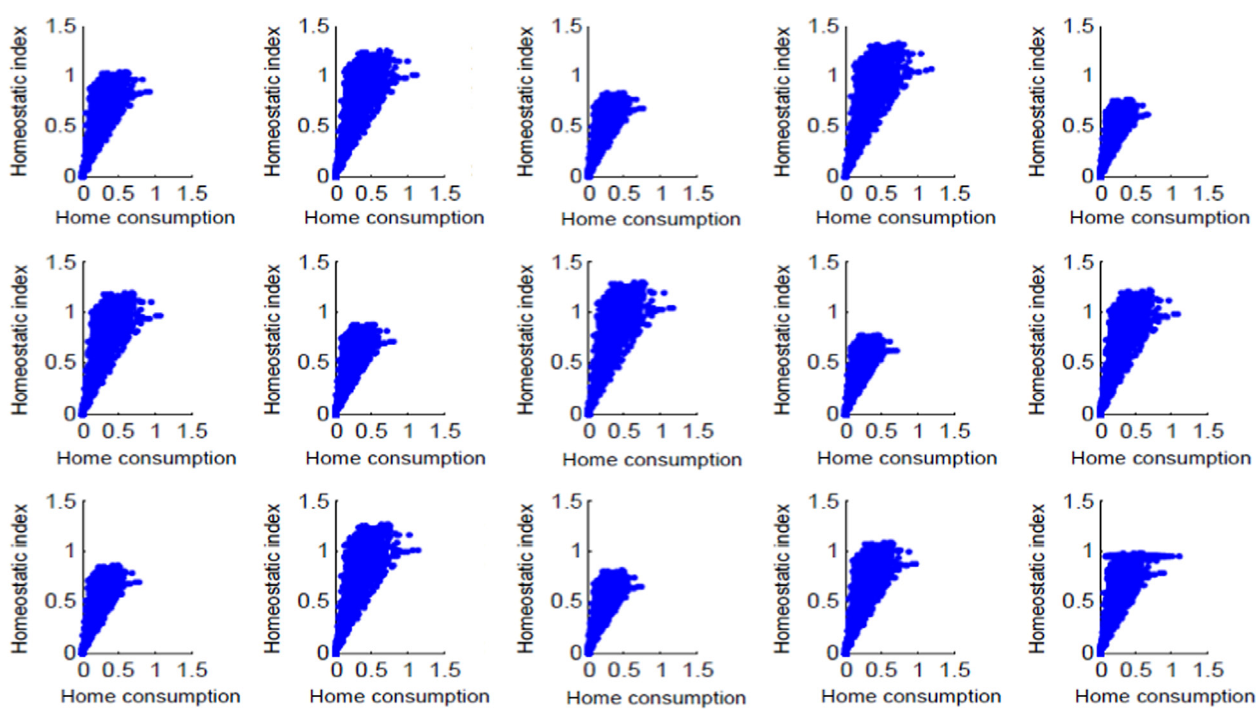

Fig. 10. H_i with energy storage case for power supply from the microgrid with Potencia_HES1, with double de amount of power supply.

internal functions and processes to achieve such state. Notwithstanding its importance, it is a concept that has been largely overlooked and underdeveloped at best in the EPS literature since it was first introduced by Schweppe in 1979 [81] in regards to electric power systems and utility–customer interaction [81–87]. Yet there is hope that there will be new breakthroughs in technology and in research which will advance HC of microgrids much further. Happily for those who aspire to see such changes in this lifetime, what seems more likely – although not within reach yet – is that over time, the balance will move more and more towards more flexible, intermittent generation, a variety of new consumer adaptation schemes for variable and differentiated power supply [5–10] and new forms of reward-based systems. These may arise as a result of new technologies such as smart metering, as they becomes a major player along with the smart grid concept. Likewise, one can expect that the application of novel, more efficient microgrids and utility grid balancing solutions will become increasingly important and more widespread within the next two decades. The concept and principles of HC in electric power systems were introduced by Schweppe and his group of collaborators at MIT [81–87] over 30 years ago. HC introduces a basic philosophy – derived from HR processes in living organisms – in which electric power generation and supply, as well as the energy demanded (the loads) by consumers, respond to each other in a cooperative fashion – conciliatory if you will – and thus are in a state of continuous equilibrium [81–91]. HR is indeed a well known and understood process, specific to every living organism, and one which has been thoroughly studied in medicine and biology [54–80]. The magic word here is adaptation or adjustment of the organism or group of organisms to changing environmental conditions, namely "*as:* (1) *adjustment of a sense organ to the intensity or quality of stimulation*,

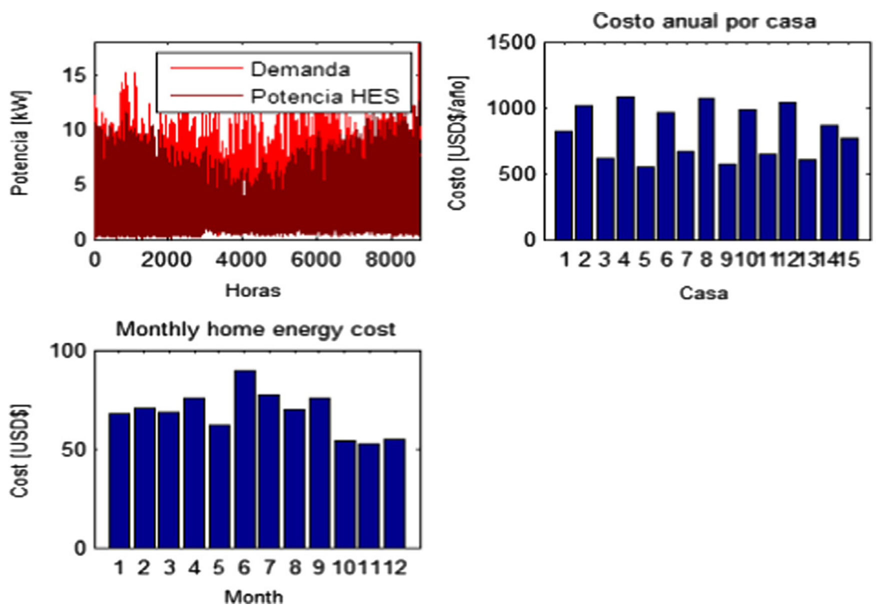

Fig. 11. Criterion 1 cost functions with HES operating at Potencia_HES RP supply capacity.

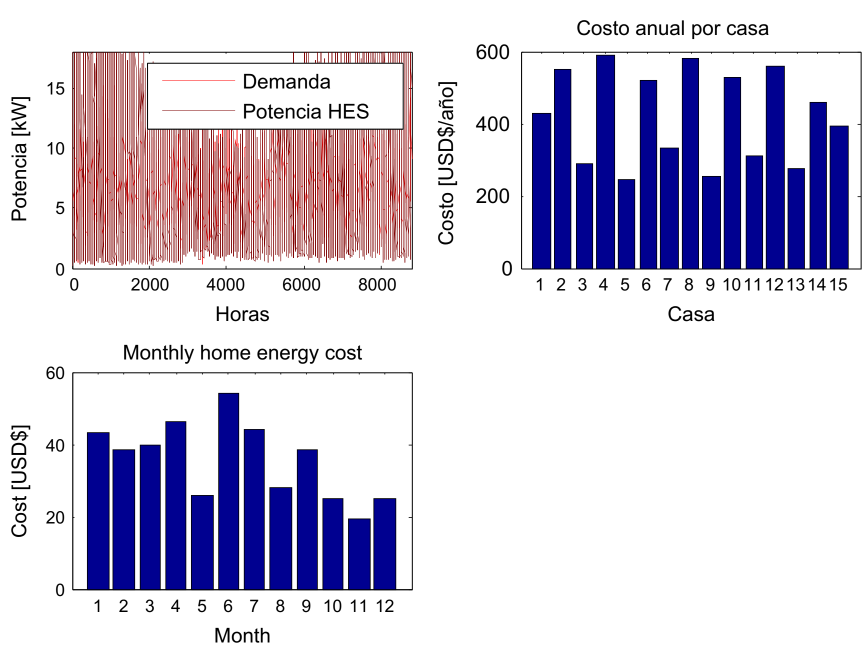

Fig. 12. Criterion 1 with the HES operating at Potencia_HES1.

(2) *modification of an organism or its parts that makes it more fit for existence under the conditions of its environment*" [55]. HR employs negative feedback, which is a primary mechanism of homeostasis whereby a change in a physiological variable that is being monitored, triggers a response that counteracts the initial fluctuation. Another important concept to be employed here is positive feedback: a physiological control mechanism in which a change in some variable triggers mechanisms that amplify the change [55,56,59]. Thus, learning from the vast experience accumulated in medicine and biology in regards to HR and HC thus far, it feels appropriate to apply this concept to EPS beyond what Schweppe and others proposed [81–91], building upon it and refocusing on micro-generation power systems integrated to the grid [5–10]. This becomes especially relevant and necessary in cases where DG solutions in the form of hybrid mini and micro-generation power systems operate tied to the grid, without energy storage [6–11]. Particularly in cases where electric power supply and EDRM aim to work together in a coordinated manner to provide a natural state of balance – a continuous equilibrium – is where one finds that HR and HC are both powerful concepts that make much sense when applied to grid-connected microgrids [28–37]. Especially when noticing that this approach goes to benefit both the electric utilities and their customers, as Schweppe and his group pointed out in their HC approach to electric power systems as well as what other authors have proposed more recently focusing on DG [5–10,81–91], wherein one can distinguish a set of interrelated physical and economic forces that strive to maintain the efficient balance between electric supply and customer load.

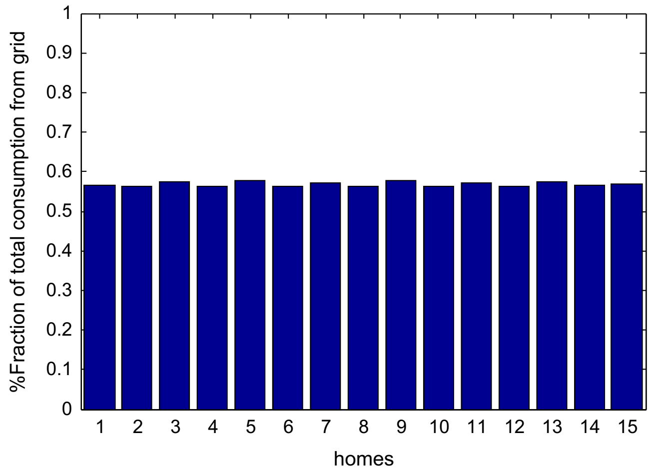

Fig. 13. Grid_Frac showing the fraction (as %) of total electricity consumption from the grid per home in the block for Potencia_HES.

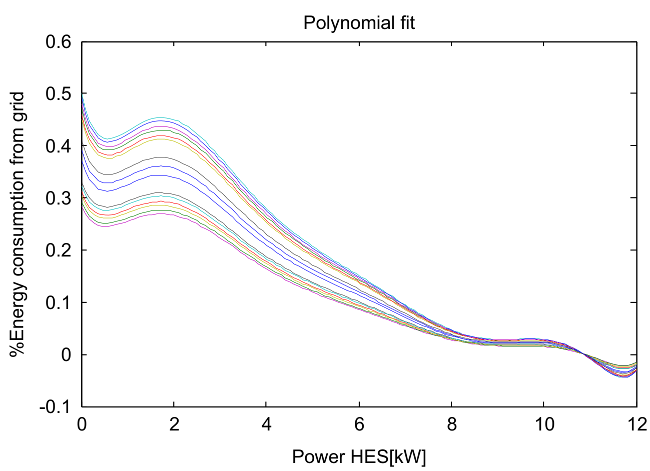

Fig. 14. Polyfit function for Criterion 1 again showing the relationship between the power consumption from the grid and the power supply available from the HES.

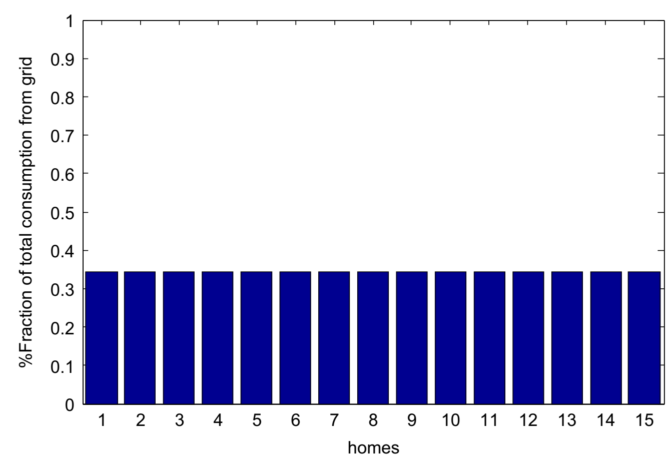

Fig. 16. Grid_frac for each home under Criterion 1 with Potencia_HES1 with absolute evenness but this time it is lower, about 35% on average for the whole block which means additional benefits.

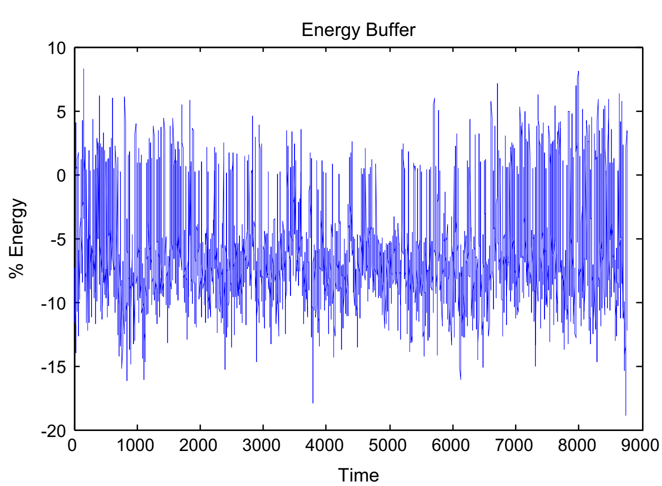

Fig. 15. Energy stored in the buffer under Criterion 1 as time moves towards the end of the one year period (8760 h).

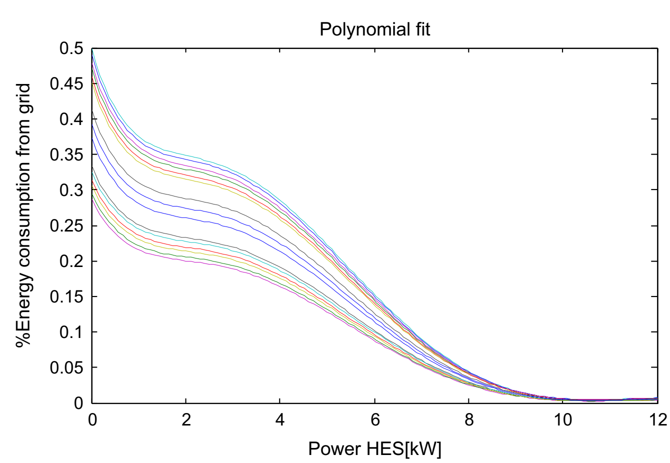

Fig. 17. Polyfit function showing a sharper drop with a softer hump, with the energy consumption (%) from Grid being close to zero near month 8.

The costs of generating electric power, along with its transmission and distribution have risen sharply, particularly in the last three decades, and the outlook for the near future does not seem to be auspicious. This harsh increase in costs and the problems of fossil fuels and their effects on the environment and climate change make the rational use of energy through EE and thriftiness and the need for more SES more important today than ever before. At the same time it makes it increasingly necessary that the allocation of energy costs falls precisely on the consumer of that energy and his/her particular energy expenditure habits. Looking at the way the consumer behaves in regards to EE and ES measures may beget other useful initiatives that could be implemented for a given community somewhere. Hence with DG solutions and new policies towards a greener, more sustainable energy outlook [39–51] which are expected to become more widespread in the developed world as well as in developing countries like

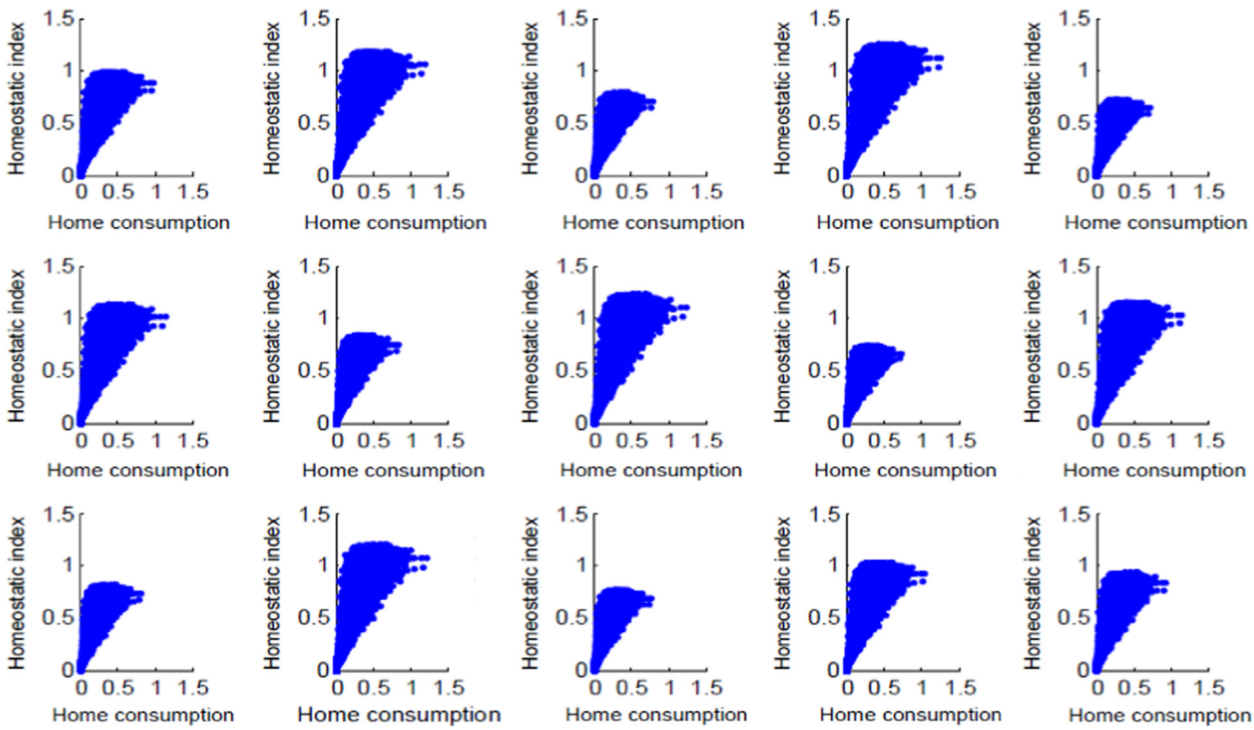

Fig. 18. Homeostatic index function H_i for Criterion 1 and Potencia_HES power supply.

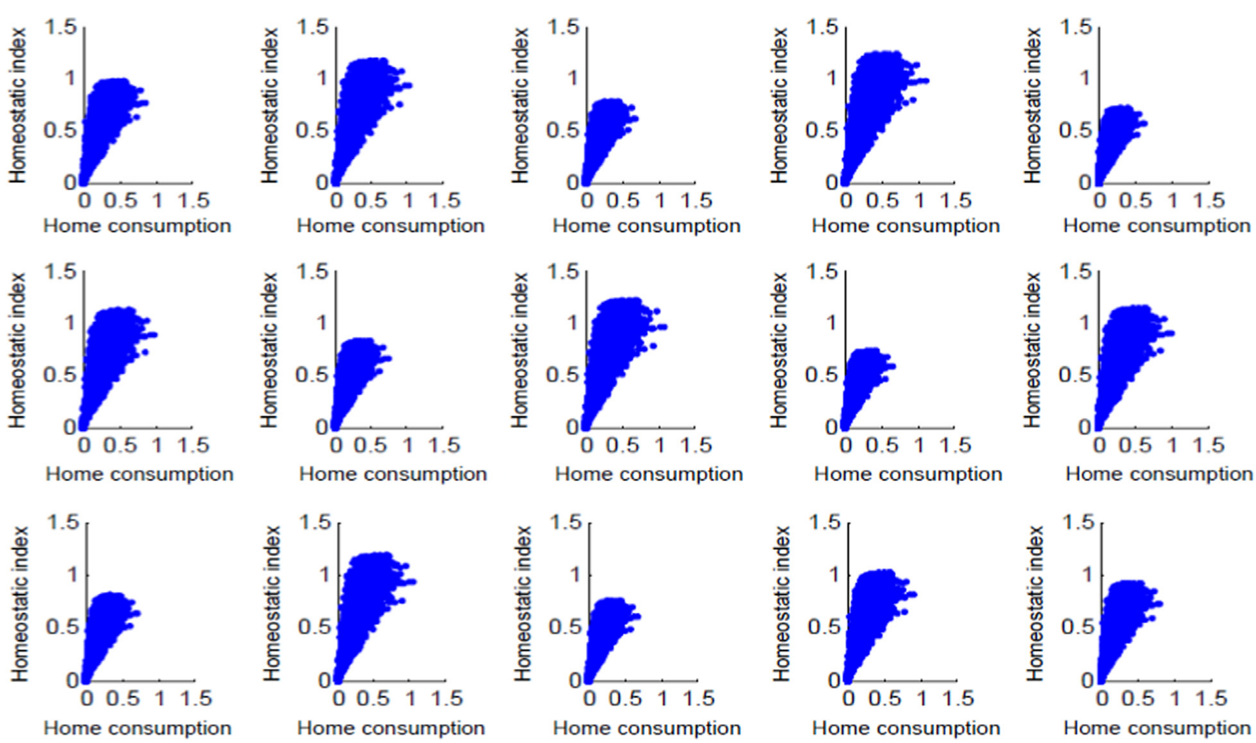

Fig. 19. Homeostatic index H_i for Criterion 1 with Potencia_HES1 (double the amount of microgrid's power supply).

Chile – a nation which aims to decouple its economic growth from its energy consumption trend – it makes sense to device efficient and effective coordination and control systems strategies like the one being proposed here in the form of HC of microgrids [5–10]. A specific model for its implementation in the supervisory control of such a system is also proposed [7]. The use of DG plants in the form of smart mini and micro-generation power systems is expected to become much more widespread and affordable in the years to come, along with new forms of control and energy management, so it makes much sense that – for the sake of equitability, economic efficiency and sustainability of such systems – one may implement control and energy management strategies that allow for a choice and flexible pricing of electricity [5–10, 88–91]. In this regard one sees that, in the general sense, the mechanism used by electric utilities everywhere has been no other than differentiated rate per time-of-day consumption. Time-of-day rates attempt to adjust the price of electric power supply to load levels based on the fact that loads behave differently at different times of the day and during different times of the year as well. Such rates however, especially in the way the system is being used today, cannot account for the advent of the new scenarios being envisaged in this paper. One where more and more DG solutions of various kinds with diverse renewable energy sources and technologies mixed with various conventional fuels and

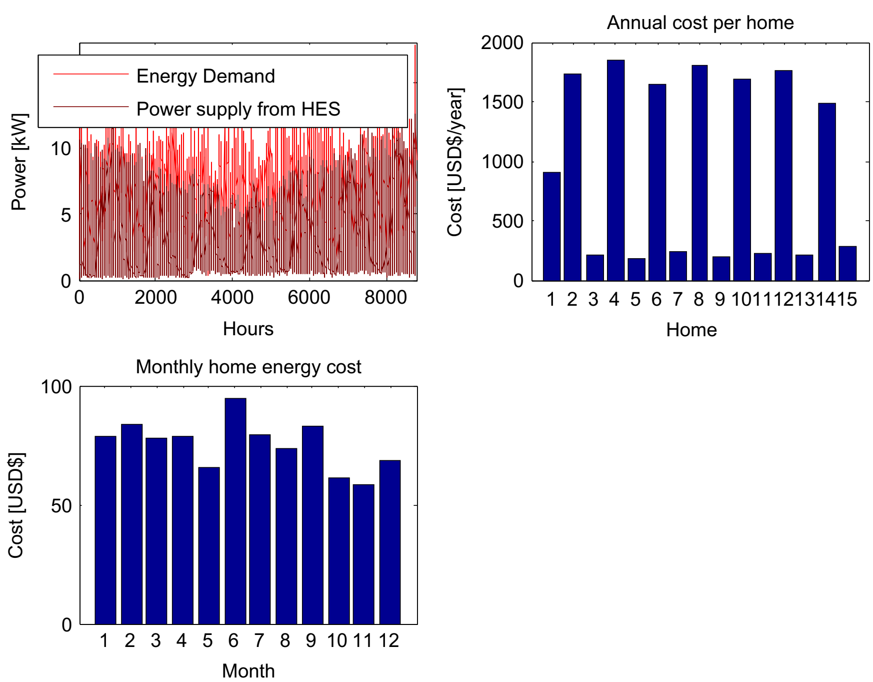

Fig. 20. Cost functions for Criterion 2 with renewable power supply Potencia_HES.

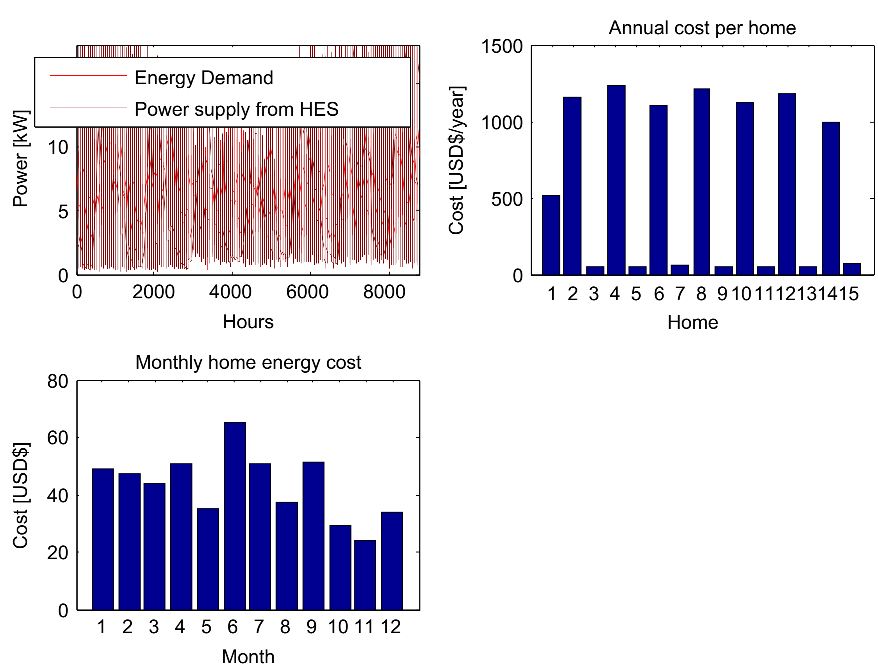

Fig. 21. Simulation of Criterion 2 for the entire block with Potencia_HES1 (double the amount).

technologies are to be integrated to the current EPS infrastructure, and the complexity that such scenario will certainly bring. Neither can they account for new, more sustainable ways of energy consumption, benefits brought about by collective behavioral changes, and how intelligent adaptive sociotechnical systems can become more resilient and capable of increasingly managing their adaptation capacity more effectively thanks to cybernetics and HC mechanisms [5–10,12,13,92–98]. Nor can current mechanism and policies used by electric utilities account for the costs nor the operating conditions that will exist once renewable power is made available on a larger scale as an option to consumers, as smart microgrids become more and more widespread. In foresight this scenario is expected to flourish in countries like Chile, where DG is expected to play a crucial role in the comprehensive energy policy strategy being sought by the last and current administrations.

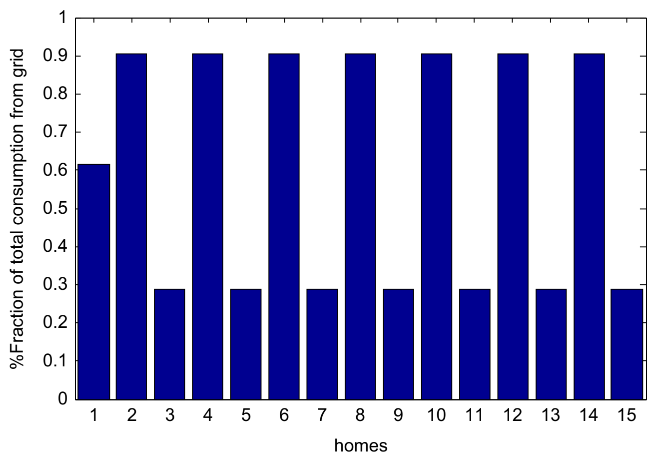

Fig. 22. Grid_Frac function for simulation of Criterion 2 with Potencia_HES where the polarization among homes is adamant and this increases as shown for Potencia_HES1.

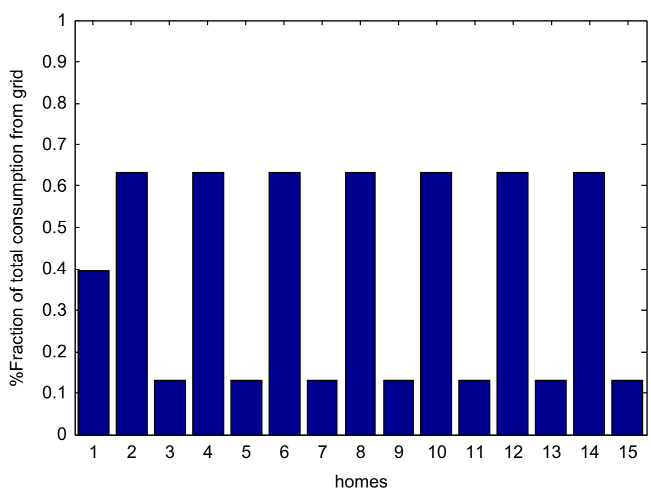

Fig. 23. Grid_Frac function for simulation of Criterion 2 with Potencia_HES1.

2.2. Energy efficiency and thriftiness in natural resources consumption

Energy efficiency and thriftiness in natural resources consumption such as energy and water, and the emergence of SES are closely linked and intertwined practices that are part of the widespread changes to come in the global energy scenario. These changes, which are already happening in several industries, will come through a number of initiatives and policies that will be seen both in developing nations as well as in the developed world. A change that society must make when faced with growing scarcity of resources and unsustainable practices that lie behind the energy obesity problem already mentioned. An important part of this upcoming global energy scenario is the technology and the local regulations that are set to dominate much of the agenda in the coming decades, wherein energy efficiency and thriftiness in natural resources consumption as well as various ES practices are expected to play a crucial role in conditioning human behavior towards this aim. These will constitute a serious push to make SES a reality and are also expected to be poignant issues ahead towards 2020 and well beyond the next decade as there are major changes to come in energy consumption and in the operation of the electric power supply infrastructure. Such changes will hopefully determine that electric power generation and distribution will become more localized, flexible and tailored to price-conscious and environmentally friendly consumers, as well as to active conservation advocates. This is to be expected especially with the increasing penetration of DG solutions such as smart microgrids and combined heat and power (CHP) systems as an alternative to the traditional electric power distribution only as it is today [5]. Energy efficiency, sustainability and environmental protection and conservation are unarguably the focus of the

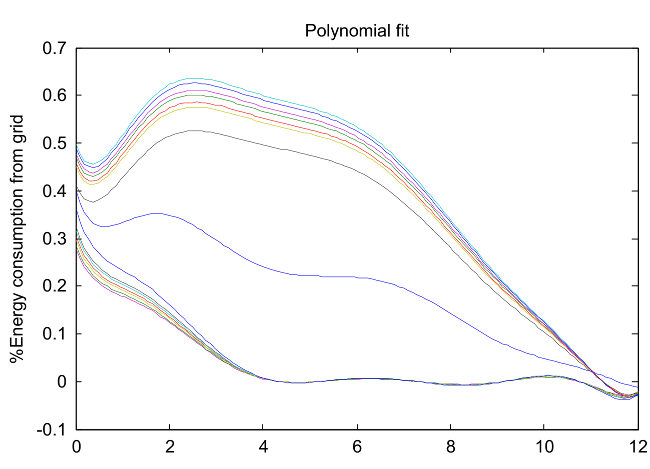

Fig. 24. Polyfit function with Potencia_HES showing a clear disparity among two groups of homes with some in between. This reaffirms the polarization shown in the prior figures for Criterion 2.

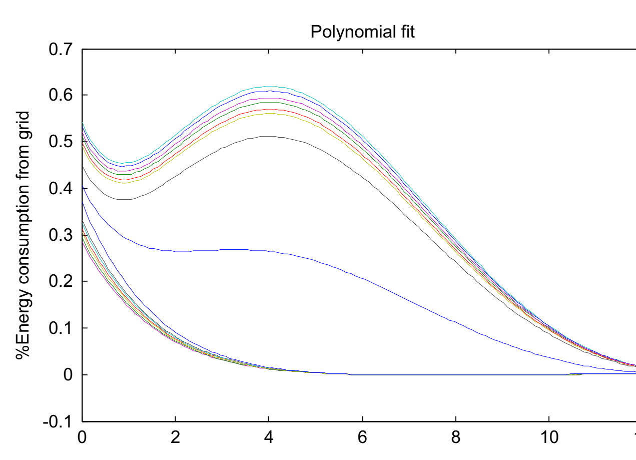

Fig. 25. Polyfit function and Potencia_HES1 showing the same clear disparity yet softer in comparison among some of the homes.

current generation as well as the focus of future generations to come in an increasingly prioritized manner in the years ahead. It is no doubt that such touchstone issues are set to dominate much of the global agenda in the next decades, where harsh rhetoric about the dire need for stronger ES measures and practices is to be expected too. In fact avoiding or delaying the measures that would elicit and bring about real change in the behavior of consumers regarding these pressing issues is rather like smoking – you know it will kill you, but you keep on doing it anyway until it is time to quit. If only one could understand the dire consequences of avoiding or delaying the decision to do something about it now, action would have been taken much sooner. Likewise, those in the leadership know about this yet cannot steer the course; at least thus far it does not appear to be happening anywhere, with only a handful of nations really taking some measures in the right direction yet very limited in scope and breadth. Again, leaders know quite well that if society does not act upon it now and breaks the habit making the change once and for all, just like smoking, it will be in a lot of trouble going forward.

3. Methodology

3.1. General approach

Three distinct scenarios were established in terms of the energy consumption demand data to be used for the simulation phase. First there is a base case scenario, where a homogenous set of demand data was established using the values of the energy

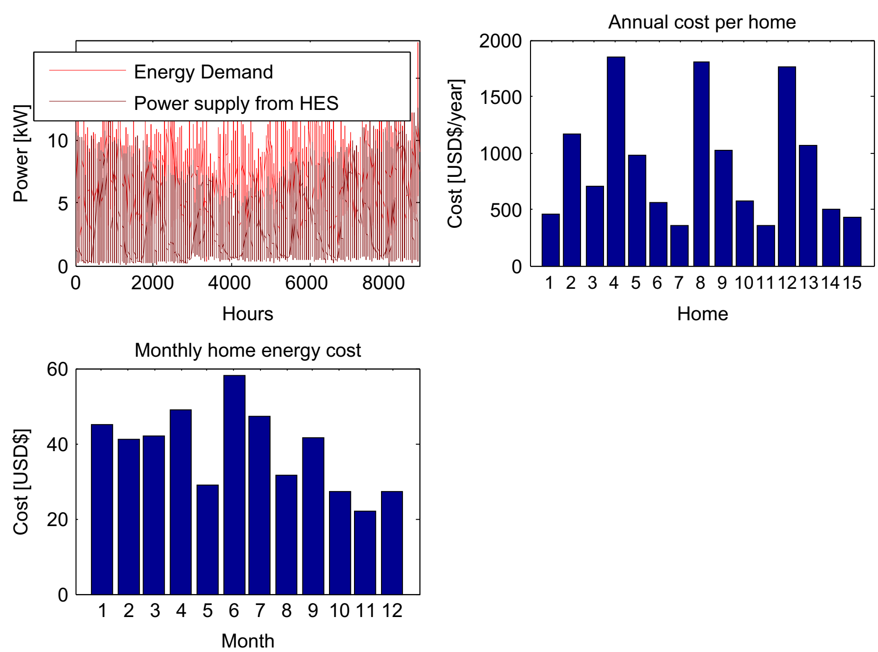

Fig. 26. Simulation of Criterion 3 with Potencia_HES costs functions.

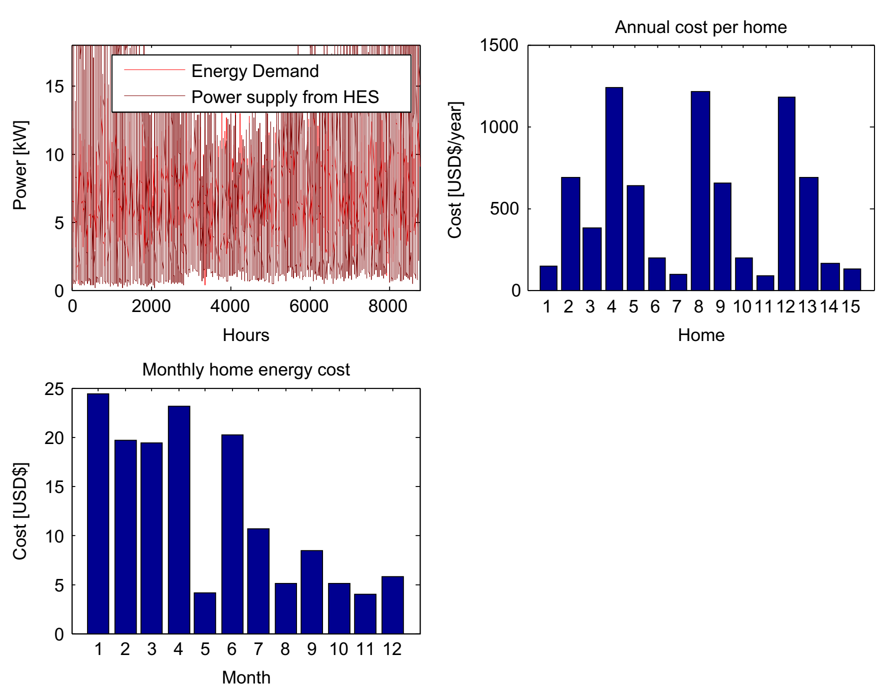

Fig. 27. Simulation of Criterion 3 with Potencia_HES1 (double the amount).

demanded by residential consumers. The values corresponded to 12 months worth of data which were then averaged and thus a new set of data was produced by varying these new averaged values over a certain range, based on the original values and their fluctuation in the target community. The data gathered corresponded to a particular rural community of Chile, quite representative of the type of rural communities that are so abundant in South America. This set of data was then randomized to produce a different set of values for what became evaluation (1) and (2) stages of the simulation phase. This average or medium case scenario is used as the base case upon which to make a comparison with the other two cases studied, producing a range of variations in the data to enhance and make more realistic the simulation efforts. The two remaining cases already mentioned are the high-difference case (2) and the low-difference case (1) where the difference between the two has to do with how wide of a difference there is in data values from the base case values in the electricity demand of consumers. For simulation purposes, a cross section of 15 homes – a sustainable block – in a hypothetical community is chosen. The low difference case (1) has small difference range values from the base case and represents a scenario of a very homogenous power consumption, quite common in some small communities, whereas the high difference case (2) is very heterogeneous, as there are larger differences in data values for the electricity consumption of the 15 homes, thus representing another type of power consumption with more heterogeneous habits as observed in other communities. Likewise the hybrid energy system (HES) was simulated extensively on a separate basis and a substantial set of values (Potencia_HES) was produced from this which presented a realistic power supply variability as a product of randomization. This allowed simulating the continuous renewable electric power generation of the microgrid, producing a set of randomized values for the power generation of the HES over a continuous time frame which lasts a complete 1-year cycle ($\Delta t = 1$ h, where $t = 8760$ h in 1 year). Finally a set of merit-based HC strategies is introduced for the coordination and control of the microgrid based on five distinct control criteria devised to enhance homeostatic regulation and control in energy consumption, assigning renewable electric power supply from the microgrid to the homes in the sustainable block only if certain conditions are met. Based on these criteria renewable power is supplied only to those homes which comply with the set criterion in an effort to influence and condition the block's electricity consumption in a way that ensures that the meta-system is sufficiently efficient and sustainable (has a higher exergy content) overtime [8,9]. In Fig. 1 there is a simple diagram that illustrates the adaptive homeostatic regulator model based on HC principles

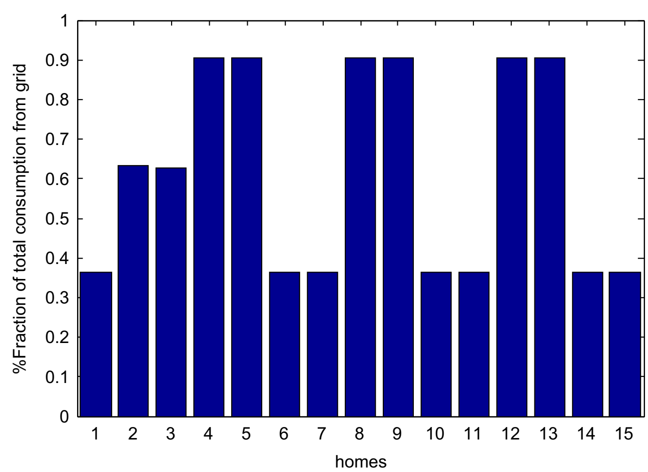

Fig. 28. Grid_Frac function for simulation of Criterion 3 with Potencia_HES.

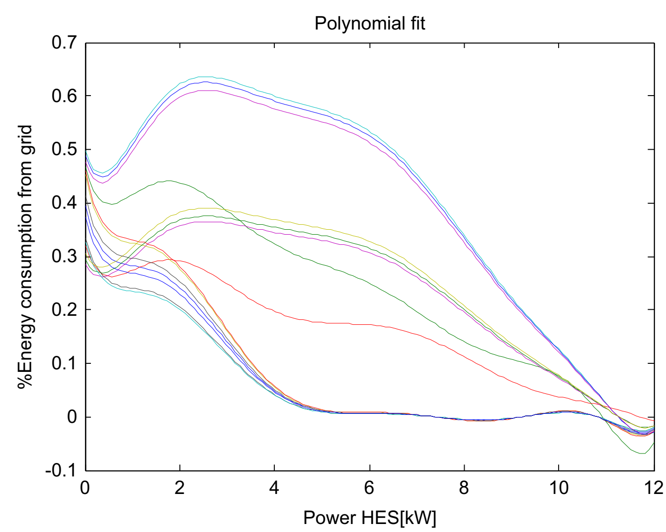

Fig. 30. Polyfit function for the 15 homes under Potencia_HES (above) versus Potencia_HES1 (below).

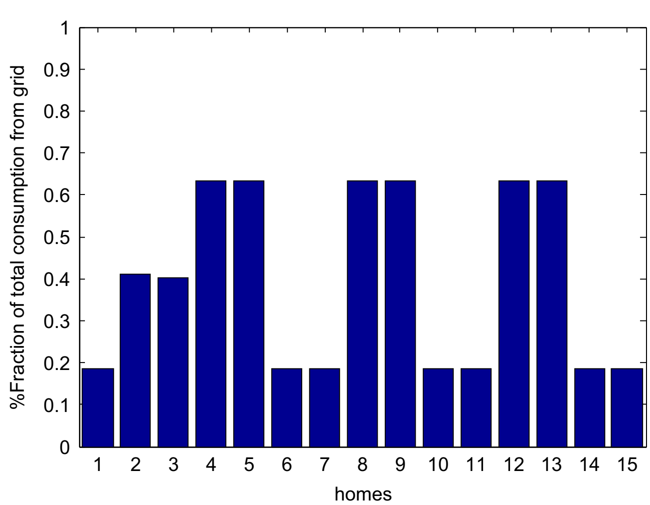

Fig. 29. Grid_Frac function for simulation of Criterion 3 with Potencia_HES versus Potencia_HES1 (double the amount).

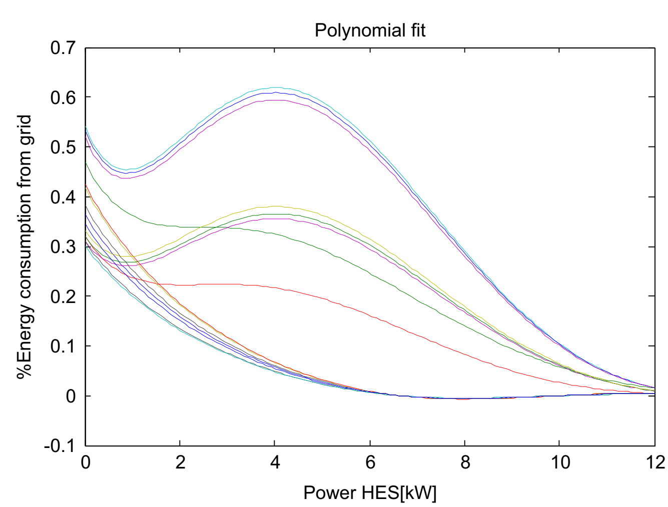

Fig. 31. Simulation of Criterion 3 with Potencia_HES1 (double the power amount).

implemented through negative feedback for residential consumers with an energy buffer.

Fig. 2 illustrates how a negative feedback control system operates with a homeostatic control scheme for a grid-connected microgrid, as a means to reconcile power supply and energy demand response management (EDRM). The key control issues here have to do with conditioning the supply of renewable power from the microgrid to the homes based on their energy consumption range. The control system strategies seek that energy users adjust their energy expenditure to a consumption range that is more sustainable for the entire block, even when they are connected to the grid. Their capacity to adapt to the changing conditions and circumstances affecting the sociotechnical system comprising the microgrid's and the sustainable block is vital in order to maintain efficient, thrifty and sustainable electricity consumption.

3.2. The role of negative feedback in homeostatic regulation (HR) of electric power supply and energy demand response management

The HC model dynamics for a grid-connected microgrid is depicted above where HR of EPS is seen as both an enabler and a driver of EE and ES. It is a core capability of the model which is ingrained in the very structure of the microgrid itself; it is built-in

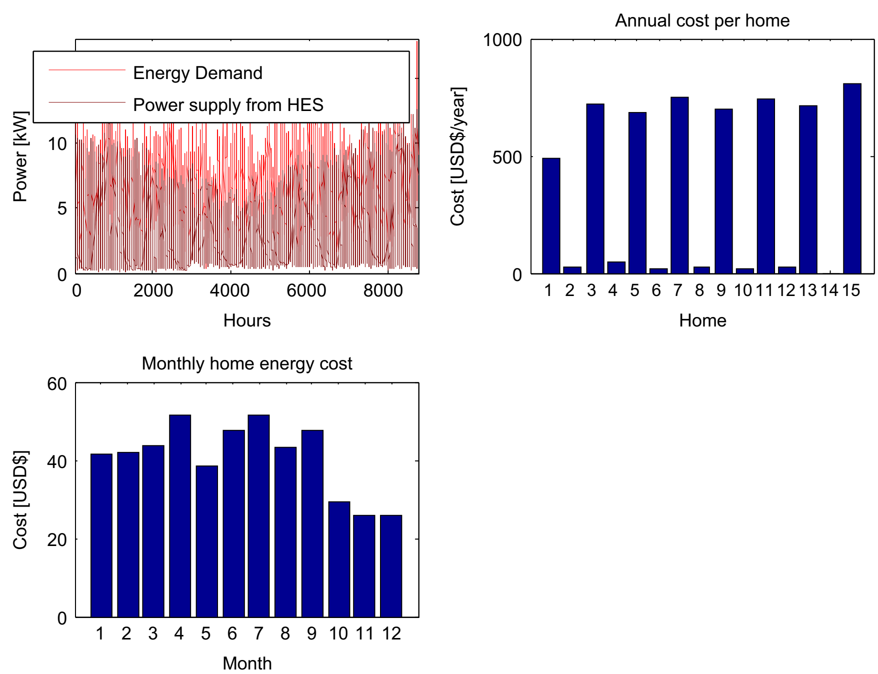

Fig. 32. Costs function for Criterion 4 with Potencia_HES versus Potencia_HES1.

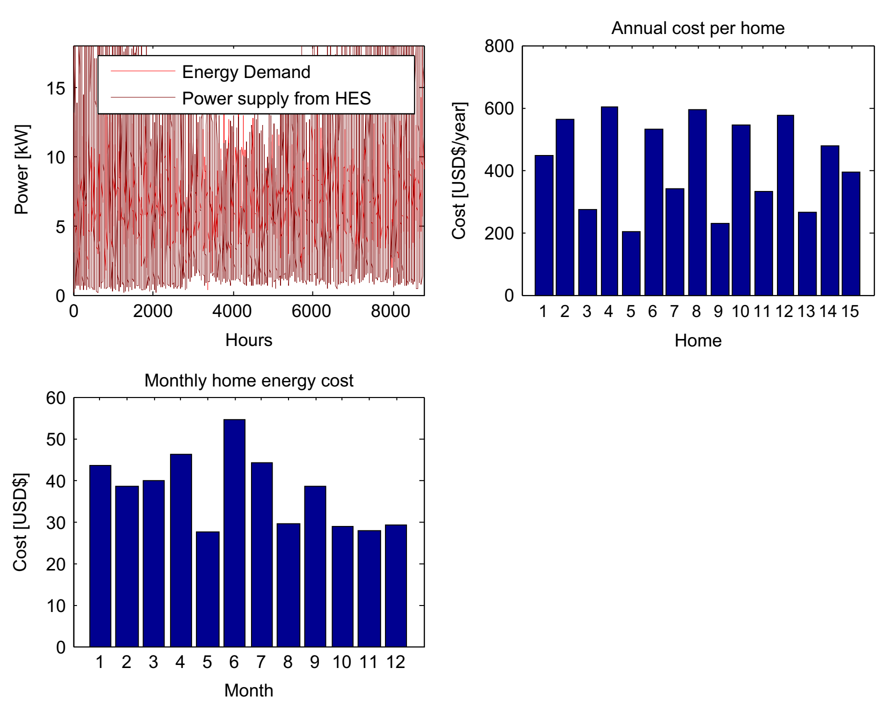

Fig. 33. Simulation results of Criterion 4 this time with Potencia_HES1.

as part of the meta-system's engineering itself. The underlying strategy aims to reconcile power supply management with energy demand and consumption management. Consumers have the option of receiving inexpensive RP from a grid-connected microgrid within limits well specified to consumers and may also get their electric power supplied by the local distribution grid throughout the day, although at a different price. Such a system should reflect the variation in costs of energy supply, brought about by fluctuations in the demand for electricity (the way energy is expended) and the particular consumption behavior of consumers (the loads) overtime [5–11]. Therefore since RP is available, although in a variable/fluctuating and limited amount throughout the day, access to its supply should not be given freely to everyone (as on a first-come-first-serve scheme) until the system runs out. Quite the contrary, as HC principles teach us, its supply should depend precisely on how effective HR is being maintained in the system considering that consumers have all the necessary information available to them by means of smart metering and are aware of the particular merit-based reward system adopted by the community. Plus they have the option of automating some of their key energy consuming tasks in the household, which may well be enhanced even further by means of energy management automation systems implemented throughout the entire community. Moreover, consumers may also have the option of having the homeostatic regulator [7] acting upon the energy supply control system management while it is reading the basic parameters of every load (the footprint), and thus it can take over at anytime, in a similar way than the FAPER [81–87] once proposed would. Thus it would work adjusting automatically their energy consumption gently so as to prevent the high cost of the monthly electricity bill. It will do so upon monitoring the residential energy needs of the block versus the energy consumption of each household under specific scenarios, and taking into consideration the power supply criterion being used therein, keeping consumption at moderate, sustainable levels. The price of electricity will be higher for those who consume more, considering the overall system's (sustainable block) load level and RP availability, both being high or low or some mix in between. Those who are thriftier and consume less will have the opportunity of getting the economic incentive of a much lower energy bill by restricting their energy intake so as to allow a larger percentage of the sustainable block to have access to RP, sharing the resource equitably and therefore an overall lower energy bill [6–10]. For this to be realized, a set of predefined criteria to elicit and instill EE and thriftiness in energy consumption among residential consumers is employed through learning and conditioning, in order to enhance their response (through positive feedback) and to use the power supply capacity of the renewable microgrid to the fullest, making the meta-system more sustainable [6–10]. These particular criteria were especially designed for the case of a small-size rural community in a region of Chile and apply the rule of merit on a reward-based system [10]. The control system keeps track of how much electricity each home is consuming at every point in time and informs consumers in their homes by means of smart

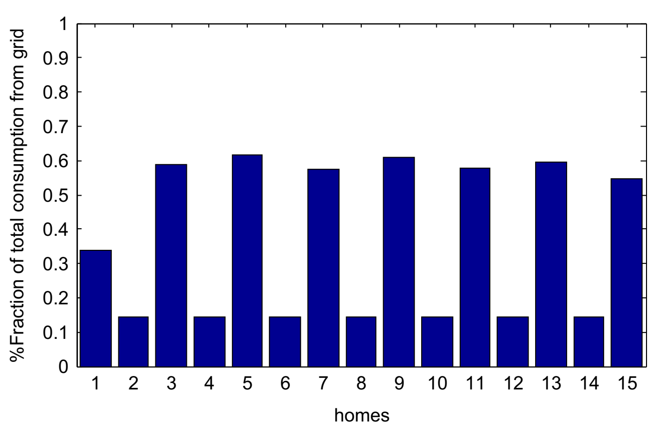

Fig. 34. Simulation of Criterion 4 with Potencia_HES versus Potencia_HES1 (double the amount).

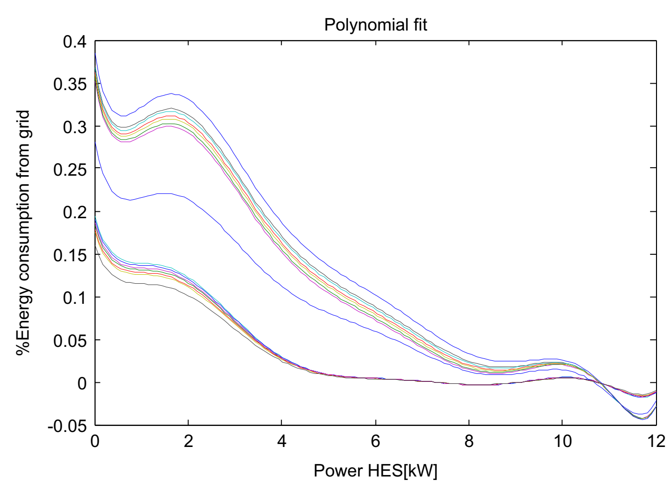

Fig. 36. Simulation of Criterion 4 with Potencia_HES versus Potencia_HES1.

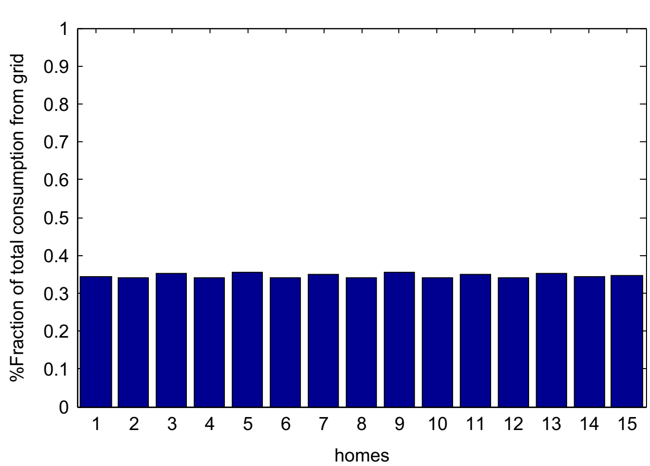

Fig. 35. Simulation of Criterion 4 with Potencia_HES1 (double the amount).

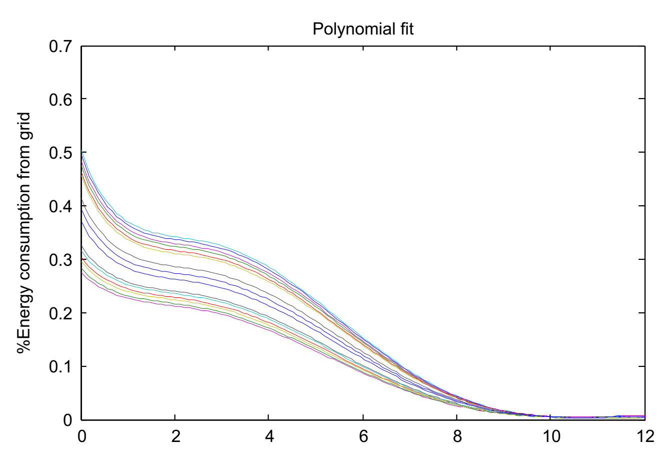

Fig. 37. Polyfit function of the entire block with Potencia_HES1.

metering. Thus the control system monitors in real time how much RP is being produced and supplied to each home by the microgrid and also how much electricity is being drawn from the grid per household. All this information is available to consumers and may also be monitored by the electric utility control operator remotely and the same for the microgrid. Every home in the block has a PLC installed in its electrical switch box. There are ongoing control signals being sent from the electrical switch box of every home (the load) to the microgrid controller via a parallel network and vice versa, from the microgrid to the homes [5–11].

Authors such as Peper state, when describing the properties of adaptive processes, that they are not the same even though they are often assumed to be synonymous whereby he makes a distinction between homeostasis and adaptive regulation arguing that the two are different [62,63]. In fact Peper [62] asserts that these concepts are very different, wherein homeostasis basically

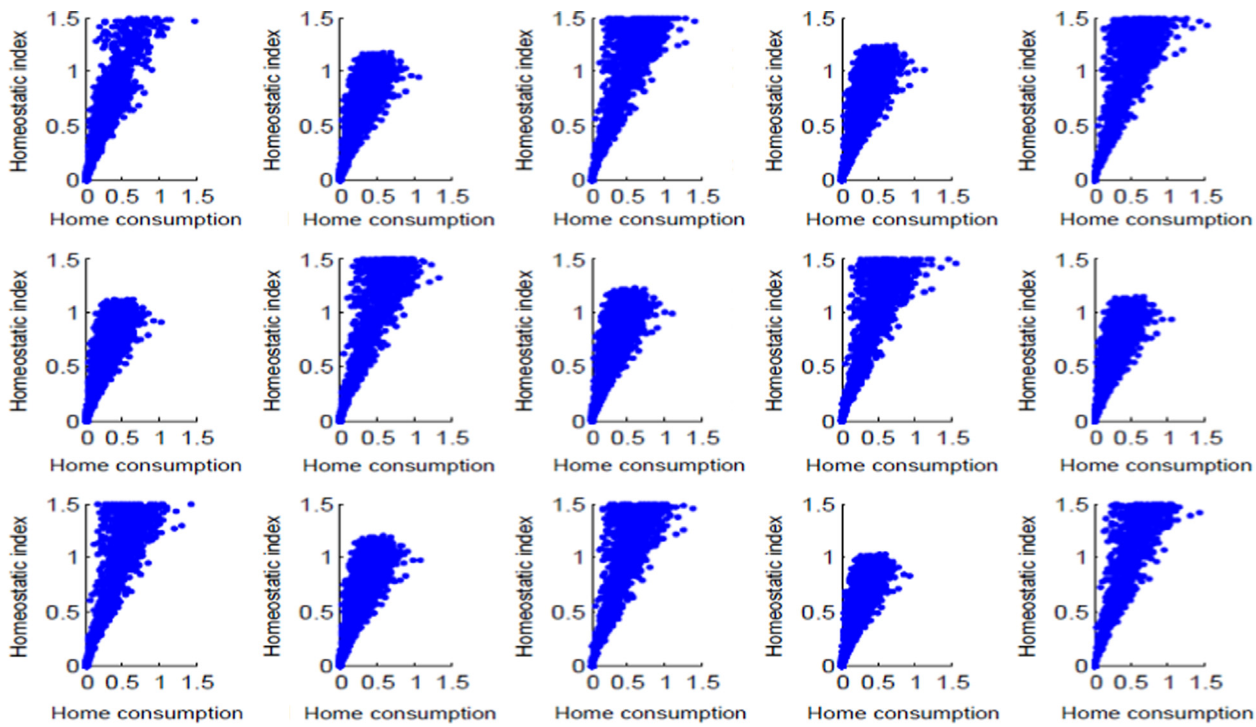

Fig. 38. Simulation of Criterion 4 with Potencia_HES versus Potencia_HES1 (shown right below).

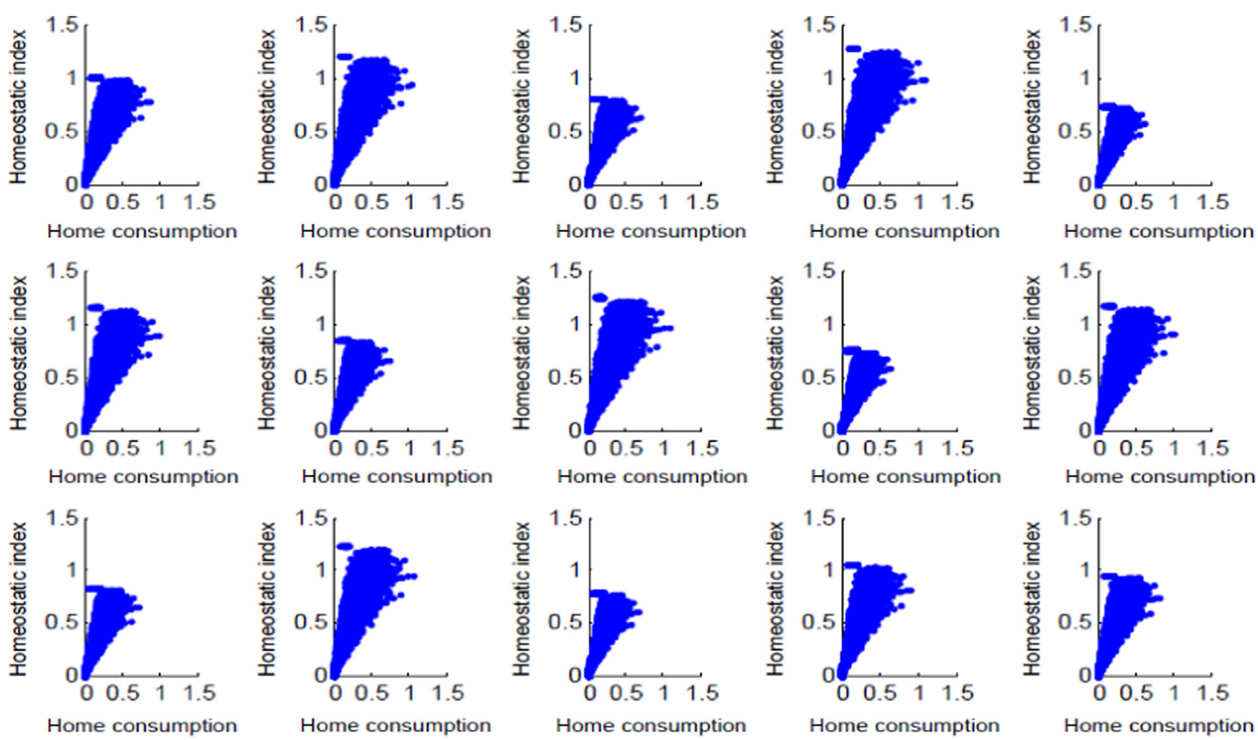

Fig. 39. Simulation of Criterion 4 with Potencia_HES1 (double the amount of power supply).

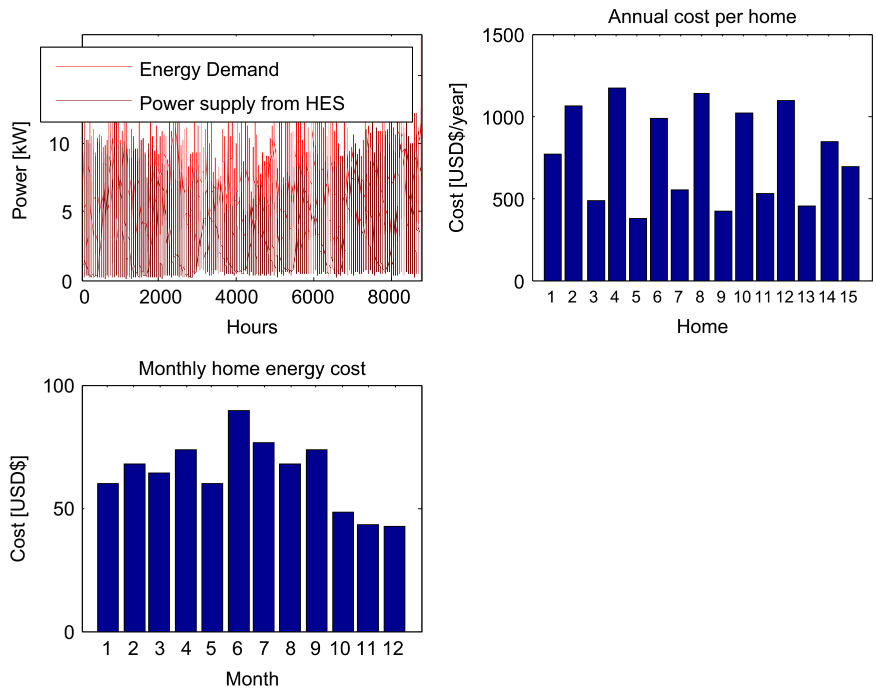

Fig. 40. Cost functions with Criterion 4 and Potencia_HES with energy buffer. *Note*: The pieces of Matlab code are not shown for the sake of brevity.

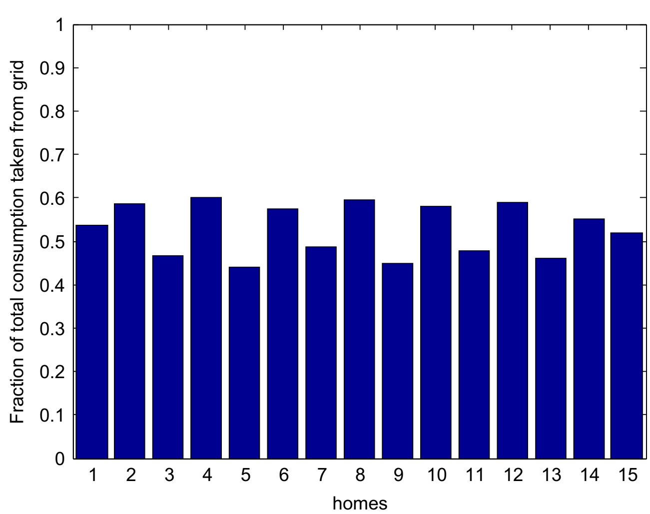

Fig. 41. Grid_frac function for Criterion 4 with energy buffer.

means that the process continues functioning at a preset level almost without change during changing environmental conditions. Yet regardless of whether the distinction made by Peper [62,63] is a valid one or not, the fact is that when it comes to the homeostasis concept introduced by Cannon [54–57] and reinforced by other authors as well on the subject with a similar stance [58–80], what Peper [62,63] calls adaptive processes which, according to him, aim for optimal performance, is precisely what HR does. Such HR in a changing environment may imply functioning at a different level or even in a different way altogether to maintain and prolong sustainability [62]. The view of this paper however is different from Peper's and contrasts sharply with his proposition. Upon focusing on HR of electrical energy in mini and micro-generation power systems tied to the grid – and the various applications which emerge from this – the concepts of homeostasis regulation are much closer to the general assertion proposed by Cannon [54] which links homeostasis with efficient equilibrium in living organisms. Particularly important in the whole scheme of things, as it will be more clearly seen later, is the role of the energy buffer (for this particular case a generic battery bank) which, together with the core capability engineered in the sustainable block (the loads) which is coupled to the microgrid and to the mains to store energy to balance both: power supply and energy consumption and storage. Hence the model proposed considers the following central elements: (1) how much electricity is being drawn from the microgrid and from the mains; (2) how much RP is being generated and supplied by the microgrid; (3) how much energy is being stored and is available in the energy buffer as a measure of energy efficiency, thriftiness and energy sustainability, all qualities driven by the HC strategy which promotes a leaner, more efficient consumption behavior; (4) a powerful new concept previously introduced [7] termed homeostatic index (H_i). It measures how much electricity is being drawn by each home from the mains as a percentage of the average total electricity (renewable plus non-renewable) being consumed by the entire block. This is being monitored and recorded in real time and shown later in the simulation results, as a report to the consumer or on a daily and/or hourly basis as preferred. H_i is basically an energy efficiency measurement linked to ES and is also an instrument that serves to evaluate the effectiveness of the HR in the meta-system at any point in time in regards to a particular criterion being employed; (5) cost indicators that allow the observer to analyze how well the reinforcement learning and conditioning is working and to assess the economic benefits derived by consumers when the whole homeostatic control strategy sets in and begins to bear its fruits. These elements are both enablers and drivers of the HR of energy in the meta-system.

4. Simulation results and analysis

Below are some of the most relevant and revealing results obtained in the simulation phase without and with energy storage. In the example used here results show that there is an intimate connection between the availability of an energy buffer in the meta-system and sustainability building. This of course is true in

the energy management of living systems just like the sustainable block, as part of the meta-system is. The literature on HR mechanisms and HC in medicine and biology is abundantly clear on this issue [16–19,54–80]. Everyone has experienced its existence and validity a great number of times in the course of a lifetime, as one goes through different periods of life changes. Hence changes in metabolic functions and factors related to age and illnesses force living organisms to accommodate to different levels of energy intake and expenditure, and also sometimes to undergo treatment to correct a dysfunction and imbalances therein. Living organisms undergo environmental and metabolic changes throughout their lifetime as well, which may at times deprive them of the proper supply of vital resources for a healthy functioning and sustenance. This condition may be accentuated much more if there are no means to buffer such deprivation or scarcity condition in the system, in order to fend off or at least going through such changes less severely. Hence the importance of the energy buffer in living organisms is undeniable, and by extension, the same applies to living systems such as the socio-technical system already described. Hence, upon running the different criteria for controlling the supply of RP from the microgrid under the different scenarios already explained, it was found that simulation provides a good fit to the data utilized, and the response of the system to changing supply under different scenarios was characterized by its consistency and logical framework, supporting the theoretical model employed [6–10]. Furthermore, results show how important HR is and the notorious difference that energy storage – the energy buffer – makes in ensuring a successful collective aim from both individual and communitarian efforts to ensure the system's overall sustainability [5–10]. Next there are the graphs for the criteria employed where only part of the illustrations are shown due to extensive set of graphs gathered. The flow diagrams depicting each of the criteria utilized, and the Matlab code programming for simulating each criterion under different scenarios were omitted, all for the sake of brevity [10]. An important point worth mentioning here is that the model presented ignores the interrelationship between power generation and transmission systems, which may be an important assumption made, as shown in several articles [99–106].

4.1. Simulation with Criterion 0: Potencia_HES versus Potencia_HES1

Potencia_HES is the standard power supply that the microgrid can generate under normal conditions, approximately 25 kW at full capacity for supplying the 15 homes sustainable block; and Potencia_HES1 is double the amount of power supply by an oversized microgrid under normal operating conditions. Another important parameter introduced here is Grid_frac which is an indicator of the fraction of total electricity drawn from the grid per each of the homes in the block. Likewise it is a measure of EE and thriftiness just like the homeostatic index (H_i) is.

Figs. 3–6 show the results of the simulation explained for each case. Fig. 7 shows the Polyfit function graph with the relationship between the power consumption of the sustainable block based on the power supply available from HES, and the power consumption from the grid by each of the homes, Grid_frac. The results for the sustainable block were obtained with Potencia_HES power supply capacity, wherein the hybrid energy system is operating at normal RP supply capacity (supplying close to 80% of block's monthly electricity needs on average). The rest must come from the Grid or from the energy buffer or both.

Next one can compare between Criterion 0 cost functions with Potencia_HES (Fig. 5) and Potencia_HES1 (double the amount of RP supply). Please notice that Criterion 0 shows less homogeneity and further polarization among residential consumers in the sustainable block as capacity doubles in the HES' RP supply. Clearly in this case there is a change downward as more renewable power supply is made available to consumers, and therefore the amount of electricity drawn from the distribution grid Grid_frac is less yet there is a further incentive for the entire block to save and to self-sustain as a collective.

In this case as it can be seen, the Polynomial fitting shows a more cohesive and regular pattern in energy consumption for the sustainable block with a maximum on month 2 (the hump).

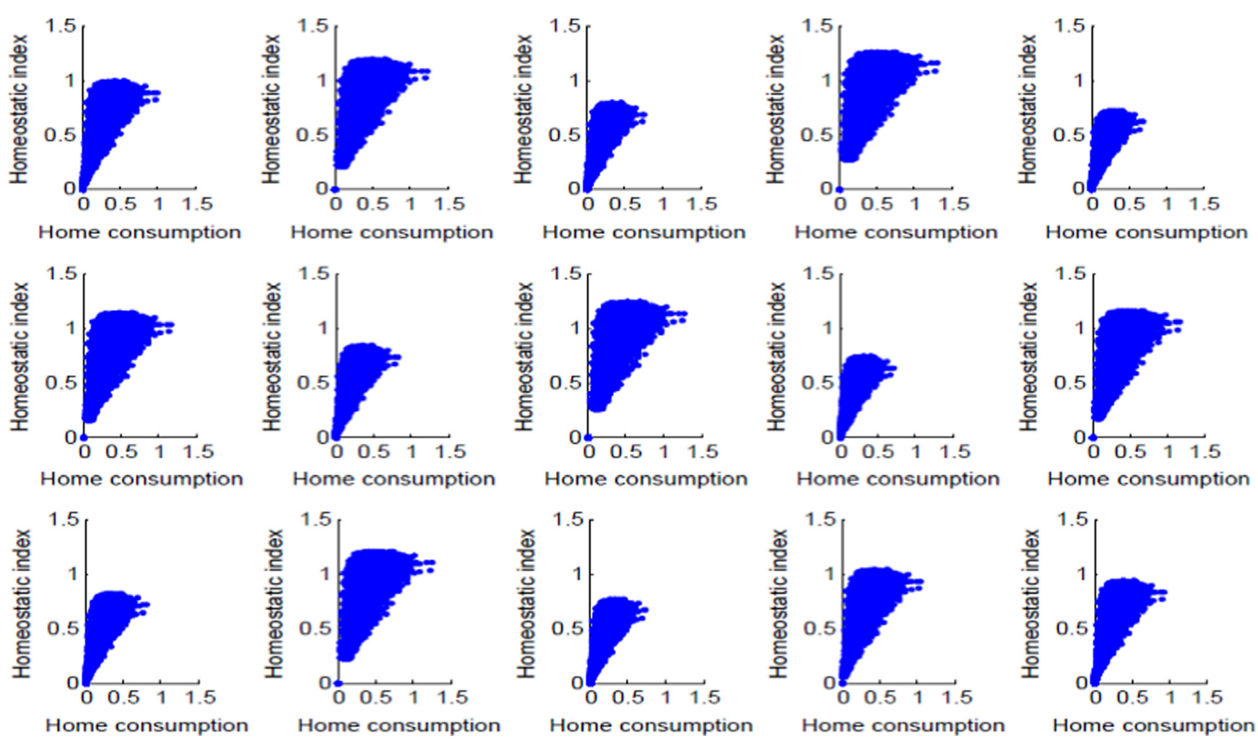

Fig. 42. Homeostatic index function showing similar benefits as those observed in the Grid_frac function for Criterion 4 with the energy buffer.

The fraction of power drawn from the grid, although behaving cohesively, decreases steadily as time goes by towards month 12, as the simulation shows. One can compare between Criterion 0 Polynomial fitting function with Potencia_HES (Fig. 7) and Potencia_HES1 (double the amount) in Fig. 8. Although similar in nature this one is softer, smoother indicating further cohesiveness in energy consumption by the whole block (Figs. 9 and 10).

Below is the H_i function shown in the case of the HES with energy storage and Potencia_HES (original amount of RP supply in kW) for the 15 homes in the sustainable block. Homes 1–5 are on the first row, 6–10 are on the second row and 10–15 on the third row. A value below 1 is considered acceptable yet ideally, values closer to 0.50 or below are a truer indicator of a high degree of thriftiness and EE for the household.

4.2. Simulation with Criterion 1 and Potencia_HES versus Potencia_HES1

In Figs. 11 and 12 one can see that under Criterion 1 the results are evidently worse than before with yet further polarization among the different homes. Thus, doubling the amount of RP supply does not necessarily guarantee a better outcome. However here is seen per Fig. 13 that remarkably there is a still uniformity throughout the entire block of approximately 55% on average. This absolute evenness although unrealistic, provides a good insight of potential RP supply strategies that may contribute to greater homogeneity and evenness in electricity consumption among residential consumers of a particular community. The case of Grid_frac for Potencia_HES1 under Criterion 1 is similar to the Criterion 0 case shown earlier yet it is more uniform and even, showing greater homogeneity for the whole residential block.

Here Polynomial fitting shows a more joint and cohesive pattern in energy consumption dropping sharply passed month 2 for the 15 homes in the sustainable block. Simulation shows that the fraction of power drawn from the grid decreases as the months near yearend. Fig. 14 is eloquent and shows the energy stored in the energy buffer as time moves towards the end of the simulation period of one year (8760 h). Here the HES is operating at Potencia_HES RP supply capacity.

Figs. 15–18 are graphs of Polyfit function and homeostatic index function H_i for Criterion 1 with Potencia_HES1 (double the amount of microgrid's power supply). Notice the difference with Criterion 0, although subtle in some cases they are nevertheless significant and revealing. Upon looking at Figs. 18 and 19, as before, no sizeable differences between the two cases emerge. Nevertheless the case with double the amount of RP supply (Potencia_HES1) by the microgrid clearly seems to make things worse when it comes to the homeostatic index, something that is counterintuitive at first but later, in light of the overall results and the theoretical support previously built [5–10], makes sense.

4.3. Simulation with Criterion 2: Potencia_HES versus Potencia_HES1

Likewise, next there are the results of some of the different functions for Criterion 2, but comparing the microgrid's base power supply, Potencia_HES, with the case of the microgrid supplying double the amount of power supply, Potencia_HES1 under same criterion. Interesting results are drawn from this simulation stage as well, some of which are not at all intuitive or predictable (Figs. 20 and 21).

Figs. 21–25 show the simulation of Criterion 2 with Potencia_HES1. Although monthly and annual costs per home are lower, the polarization among electricity consumers clearly still shows and not only maintains itself but deepens further for the case of Potencia_HES1, again a very revealing yet counterintuitive result altogether. Likewise it is seen with Grid_Frac function for simulation of Criterion 2 that the polarization among home consumers deepens, with a group distancing from the other with the exception of home 1(being a middle-of-the-road case) yet the fractions are lower as shown below.

4.4. Simulation with Criterion 3: Potencia_HES versus Potencia_HES1

Below is Grid_Frac function for simulation of Criterion 3 with Potencia_HES versus Potencia_HES1 (double the amount). Again one may see that the polarization among home consumers remains, but in this particular case with a different pattern – odder if you will. Upon employing this particular criterion, two types of consumers clearly emerge yet some residential consumers escape from this polarization like homes 2 and 3. Likewise one may see by looking at Figs. 26 and 27 that costs are indeed lower in Fig. 27, yet at a cost of less homogeneity and further polarization among consumers (Figs. 28–34).

4.5. Simulation with Criterion 4 Potencia_HES versus Potencia_HES1 but without energy buffer

Below there are the Criterion 4 graphs (Figs. 35–42) comparing the results of Potencia_HES with Potencia_HES1 for the case without the energy buffer. Fig. 33 shows simulation of Criterion 4 with Potencia_HES1 (double the amount). Here things worsen as costs clearly do not improve as the amount of RP supply is doubled. Surprisingly at first, Criterion 4 like Criterion 3 works better in regards to Grid_frac function when power supply is increased to double the amount. A more homogenous and efficient electricity consumption behavior among consumers is seen without extreme polarization and lower costs for individuals, and for the entire sustainable block. Indeed Criteria 3 and 4 seem to work better at this than Criteria 0, 1 and 2 seen earlier.

Here the Polyfit function in Fig. 37 shows that the behavior of the entire block with Potencia_HES1 seems more favorable, with a better response, more evenly tight and homogenous unlike with Potencia_HES. Interestingly, unlike Criteria 0, 1, and 2, here one sees that there is a clear improvement with Potencia_HES1, showing a much better system response – with higher energy efficiency and thriftiness – of the Grid_frac function in this particular case. A fact that shows that for this particular criterion it is beneficial to have more power supply available from the microgrid (an oversized microgrid capacity) in terms of the response of the sociotechnical system as a whole.

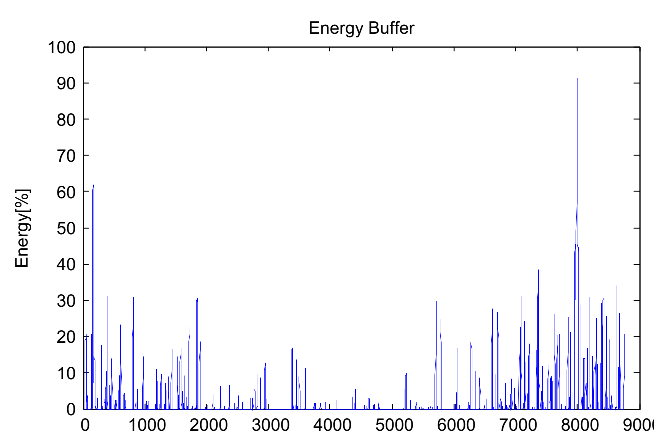

Fig. 43. Energy percentage in the energy buffer as time (in h) goes by towards a full one-year cycle.

4.6. Simulation results of Criterion 4 with the energy buffer

Next (Figs. 43–45) there are the simulation results of the different functions for Criterion 4 but this time with the energy buffer present. Particularly interesting are Figs. 37 and 38 which, along with Figs. 43 and 44, show the response of homeostatic regulation (HR) in the energy consumers, enabled and driven by the HC strategies in the sustainable block. Revealingly, the results show that consumers are more willing and able to save energy, allowing more energy to go to storage in the buffer, when the buffer is present in the system than if it were not. Clearly some homes are more energy efficient and thriftier than others yet the desired overall response of the system is far less polarized than before. A more homogenous and even response by consumers is observed in this case, with homeostatic regulation being more active as expected.

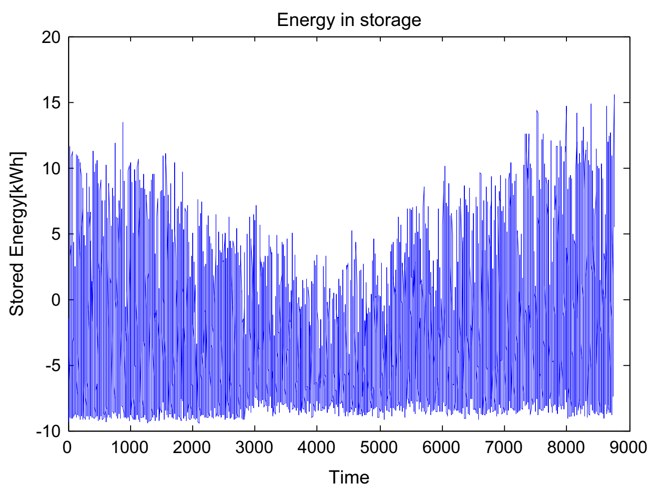

Fig. 44. Eloquent, shows the energy stored in the energy buffer as time moves towards the end of the simulation period of one year cycle (8760 h).

4.7. The same simulation analysis but this time with Potencia_HES1 (double the amount of RP supply) available to the block

Analogous to the previous cases, in Section 4.7 a sample of simulation results is shown this time with Potencia_HES1. At this stage of the simulation phase a sizeable improvement was appreciated in the case of Potencia_HES1 power supply as opposed to Potencia_HES, with the energy buffer present in the system. The fraction of electricity drawn from the Grid by the 15 homes in this case is substantially lower than before. This is intuitively sound and reasonable if examined closely based on what was learned previously. Also worth mentioning here is that when Potencia_HES was increased even further results (not shown for the sake of brevity) were even less effective in terms of HR index and the strategy to elicit EE and thriftiness was undermined as expected.

This again reaffirms the thesis that increasing beyond a certain point the power supply in the microgrid with the presence of energy storage does not aid in improving the HR mechanisms but rather hinders them. Homeostatic regulation (HR) in the sustainable block being fully active, shows that consumers are more willing and able to save energy allowing more energy to go to storage in the buffer, knowing that it will be available for them.

5. Conclusions and final remarks

With regard to responsive demand and demand side management [107–109], particularly when it comes to residential energy supply and consumption at the mini and micro-generation levels operating connected to the grid, it is not the same to have or not to have energy storage systems present in the microgrid [52,53]. To anyone this may seem trivial at first glance yet here one should not simply refer to its role as an energy back-up system for electricity storage and dispatching in DG solutions as important as that is. What is even more important than the supporting or back-up function already mentioned is the role that the energy buffer plays in the energy homeostasis regulation processes within

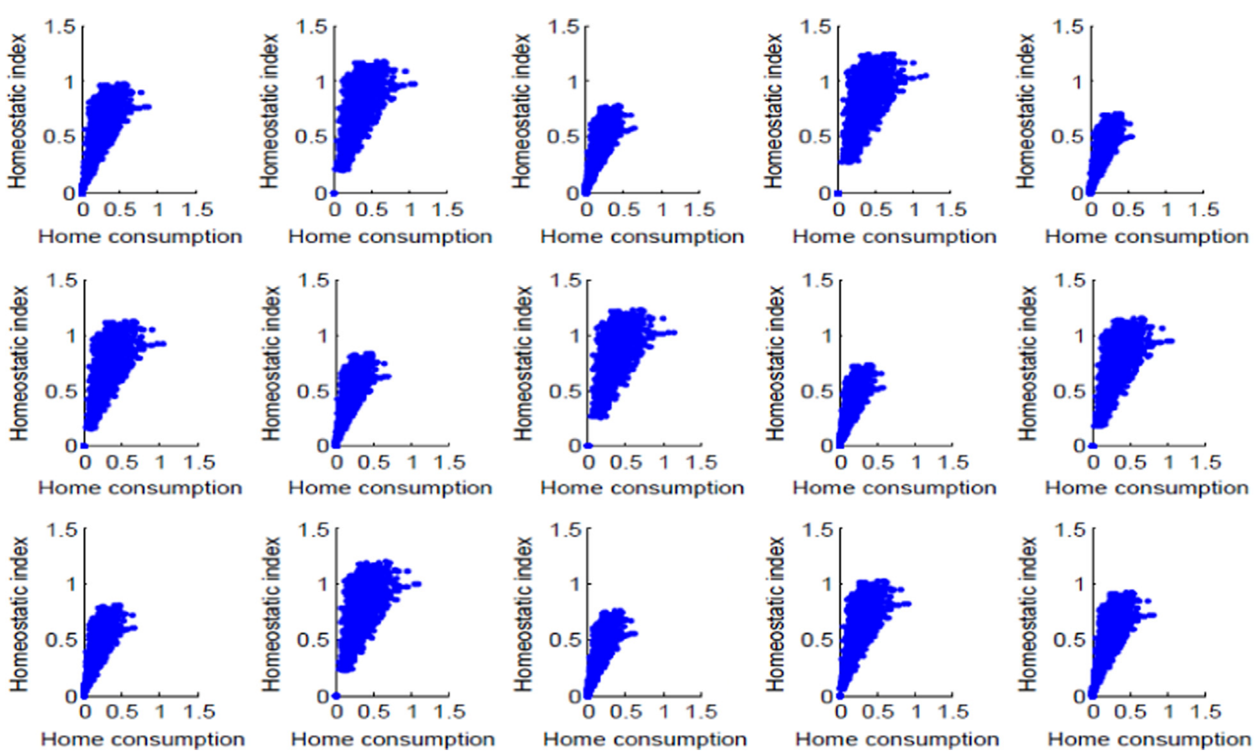

Fig. 45. Another favorable response is observed this time by the homeostatic index function although not better than with Potencia_HES.

the meta-system, as a key enabling technology of EE and thriftiness that have been previously discussed extensively. Unlike what you would normally think, for reasons that are not readily apparent, if one is trying to instill the desired behavioral changes, i.e. to enhance and potentiate EE and thriftiness in residential energy consumers to produce a virtuous cycle that feeds and builds upon itself, the energy buffer may prove to be a key enabler and also a driver of such traits. When it comes to HR in energy consumption and the ability to transform the average electricity consumer in a community into a more energy-conscious and carbon neutral individual, having energy storage may prove vital. Indeed the ability to change towards a thriftier, greener and more energy-sustainable consumer depends greatly on the awareness of energy storage availability in the system and the crucial role that it plays in the HR process. When it comes to really making a big leap forward in energy systems sustainability and EE, it does matter whether there is or there is not an energy buffer in the microgrid system, and – contrary to common credence – more so if the microgrid is grid-connected than if it is not, operating only as a stand-alone (island mode) system. A battery bank is a fast-response energy storage technology (is readily dispatchable) and for the purpose described earlier, it can effectively act as an energy buffer in the HC strategic scheme already discussed. Furthermore if smart metering is added to every home, one has effectively built energy sustainability in the meta-system, i.e. a sustainable hybrid energy system [7,10]. Again, it is here that one sees this virtuous cycle emerge again, where the energy buffer comes into play by means of negative feedback to consumers (the brain of the system) advising them of how much electricity is being produced by the microgrid, how much is drawn from the grid and how much is available in storage and what is being supplied by the energy buffer. With this information available, the system works well and is capable of eliciting EE and thriftiness in energy consumption with a clear economic incentive for consumers to be able to save and thus to use less grid power supply or to sell the excess energy back to the electric power distribution system if the local legislation were to allow so and still live comfortably and sustainably. In this way it is not necessary for consumers in their homes to go beyond their limits or to have the opposite effect, being overly thrifty, just like it is seen in cases of energy shortage regimes as in the case of dieting, so as to warrant major energy saving by an individual's metabolism. This is exactly the undesirable backfire effect which is unwanted. This is what happens when an individual (or the consumers in the sustainable block for that matter) is put on a strict low-calorie, low-energy intake diet without adequate and periodic food intake. This makes the individual clutch onto the weight desperately, trying to maintain equilibrium by means of HR, and thus preventing him from gradually losing the excess weight by becoming accustomed to lesser food (energy) intake and availability. This smooth transition is necessary over a certain period of time both by dieting and mentally adjusting his/her metabolism to the changes brought upon the system and it should be realized according to the particular physiology and age factors of the individual or, in the case of a small community, according to its particular characteristics as a community. Something that requires reinforcement learning and conditioning upon which the individual builds strength to change his/her energy consumption behavior overtime, signaling the brain that he/she is doing fine and handling the diet regime well, having enough energy storage at his disposal. Therefore he/she can successfully continue to make progress without triggering the alarm or warning signal in the system, aimed at tightening the body's metabolic functions to reduce to a minimum the energy expenditure, preventing the person from losing the weight. Therefore, as simulation results suggest, when consumers have the security and reassurance of having an energy buffer and strive to support it with their consumption behavior, building reserves that can later be used or sold to the electric utility grid, the ES cycle works and the strategy is successful. Again, the wonder-like mechanism at play here is the same that operates in humans who are put on a diet with adequate food intake and expenditure as discussed before. This is true also in other living systems that are made aware that there are enough resources available to them in the environment, so they can safely exercise restraint, thriftiness and energy efficient behavior without overdoing HR in a way that overstrains the system to a point where living conditions are compromised. With this in mind the microgrid system is moving towards the attainment of a new, safer and more sustainable equilibrium point – one that is conditioned by the presence of the energy buffer operating in the grid-connected microgrid.

Upon looking at the overall results of the simulation one concludes, as expected, that the costs of electricity when the grid is present are quite relevant whenever there is an option present to receive RP as well as the grid's power supply. This in return for a change in consumption behavior. Likewise there is a very distinct scenario in terms of whether employing energy storage or not in terms of the microgrid capacity to influence the way consumers behave towards energy and sustainability. The first main result is that there are indeed certain criteria under distinct scenarios, which work better than others at making the meta-system performance better in terms of thriftiness and EE towards ES. Nevertheless, the choice of which criterion to employ will depend largely on the community's energy consumption habits and historical patterns of electricity usage and peak loads, along with local RES and the availability and electricity price of a local power distribution grid to which the microgrid can connect. Performance is measured by the homeostatic index and the grid fraction as well as by the amount of energy being saved in the energy buffer as a result of the thriftier, more efficient energy consumption behavior of the sustainable block as a function of the HC strategy in operation. The cost for consumers in their monthly electricity is significantly lower as they are able to use more RP and less; grid power, thus reinforcing the behavioral change being sought. For each criterion there is a distinct response of the system, and these responses in terms of monthly cost to consumers are also different, as parameters change, proving the efficacy of certain parameters over others, particularly in Criteria 2, 3 and 4. The second main result concerns the evolutionary response of the block's electricity consumers in the presence of the energy buffer, through the properties of dynamically complex adaptive systems comprising the meta-system already described. It is in this context that one must stress once again the vital role that these energy users ought to play and what their response will be as a collective to temporary environmental perturbations therein.

The third main result is that upon increasing the RP supply from the microgrid to double the amount being supplied, no significant change in thriftiness and efficient energy consumption was shown by the simulation except for Criteria 3 and 4 where homeostatic index and Grid_frac as well as the Polyfit function clearly make a positive difference. This suggest that – at least in theory – increasing the capacity of the microgrid or adding a bigger capacity energy storage does not equal automatically to better results, as they might not always enhance or stimulate homeostatic regulation and thriftiness but may even hinder it. Results show that a positive or negative response of the meta-system is very homeostatic control-strategy dependent and this in turn ought to be designed and engineered with the particular community's characteristics in mind.

Finally there is the fourth main result, which comes as a reflection, upon looking into the not so distant future. One in which climate change, natural calamities and vandalism may become ever more frequent bring chaos and havoc upon modern society's infrastructure, undermining the power supply and other

vital services in more serious ways than what has been seen in the past [5]. A future, for which the present electric power infrastructure is clearly unfit, as it needs to become much more flexible, nimble, localized and diversified [5]. Hence, when looking to what future developments of DG integrated to the current electric power distribution might bring, it is believed that it will become necessary, in order to effectively build SES, to pursue innovative coordination and control strategies such as the one proposed here based on HC of grid-connected microgrids. Such strategies may offer innovative mechanisms for the control of the RP supply to consumers with a reward-based system that fosters and impels a merit scheme feeding on positive reinforcement for the whole community as part of a meta-system. However, for such reward-based system to elicit real and lasting change in energy consumption behavior there must be clear economic as well as non-economic incentives present in such merit scheme. This in order to effectively secure and potentiate an adequate energy management in terms of electricity supply and consumption. In return energy users can be rewarded for doing so by receiving inexpensive RP instead of having to buy expensive electric power from the grid as their only option. It is the goal of this and other papers before it [5–11] that such strategies linked to EE and thriftiness can be used in the design of such DG systems to elicit and ultimately bring about this much sought-after change in consumer behavior and, in the process, create the opportunity to open the way to a whole new concept in the way energy is used based on homeostasis. However, as one can expect when it comes to such big leap forward, the plight for such a change will not be easy. In fact and very likely, it will be an uphill road and a very steep one.

Acknowledgments

This work was supported in part by the Comisión Nacional de Investigación Científica y Tecnológica, CONICYT of Chile under the doctoral fellowship of the first author.

References

[1] Cifuente LA, Jorquera H, Sauma E, Soto F. International CO-controls analysis program final report. Santiago: Pontificia Universidad Católica de Chile; 2001.

[2] Norero J, Sauma E. Ex-ante assessment of the implementation of an energy efficiency certificate scheme in Chile. J Energy Eng – ASCE 2012;138 (2):63–72.

[3] Munoz F, Sauma E, Hobbs B. Approximations in power transmission planning: implications for the cost and performance of renewable portfolio standards. J Regul Econ 2013;43(3):305–38.

[4] Energy Technology Perspectives 2012. International Energy Agency (IEA). [released 11.06.12].

[5] Cordova FM, Yanine FF. Homeostatic control of sustainable energy grid applied to natural disasters. Int J Comput Commun Control 2012;8(1):50–60.

[6] Yanine F, Cordova FM. Homeostatic control in grid-connected micro-generation power systems: a means to adapt to changing scenarios while preserving energy sustainability. In: Proceedings of the IEEE International Renewable and Sustainable Energy Conference (IRSEC); 2013. p. 525–30.

[7] Yanine FF, Sauma EE. Review of grid-tie micro-generation systems without energy storage: towards a new approach to sustainable hybrid energy systems linked to energy efficiency. Renew Sustain Energy Rev 2013;26:60–95.

[8] Yanine FF, Sauma EE, Cordova FM. An exergy and homeostatic control approach to sustainable grid-connected microgrids without energy storage. Appl Mech Mater 2014;472:1027–31.

[9] Yanine FF, Sauma EE. Linking exergy and homeostatic control to develop sustainable grid-connected microgrids. In: Proceedings of the ChileCon 2013, IEEE conference in Santiago, Chile & international microgrid symposium 2013. Santiago, Chile; 9–12 September 2013. ⟨http://der.lbl.gov/microgrid-symposiums/santiago-2013⟩.

[10] Yanine FF, Caballero FI, Sauma EE, Córdova FM. Homeostatic control, smart metering and efficient energy supply and consumption criteria: a means to building more sustainable hybrid micro-generation systems. Renew Sustain Energy Rev 2014;38:235–58.

[11] Caballero F, Sauma E, Yanine F. Business optimal design of a grid-connected hybrid PV (photovoltaic)–wind energy system without energy storage for an Easter Island's block. Energy 2013;61:248–61.

[12] Geels FW, Schot J. Typology of sociotechnical transition pathways. Res Policy 2007;36:399–417.

[13] Geels FW. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res Policy 2004;33(6):897–920.

[14] Alling A, Nelson M, Leigh L, Frye R, Alvarez-Romo N, MacCallum T, et al. Experiments on the closed ecological system in the Biosphere 2 test module. Ecological microcosms. In: Odum HT, Beyers R, editors. New York: Springer-Verlag; 1993. p. 463–79.

[15] Marino BDV, Odum HT. Biosphere 2, introduction and research progress. Ecol Eng 1999;13:314.

[16] Weyer C, Walford RL, Harper IT, Milner M, MacCallum T, Tataranni PA, et al. Energy metabolism after 2 y of energy restriction: the Biosphere 2 experiment. Am J Clin Nutr 2000;72(4):946–53.

[17] Walford R, Mock D, Verdery R, MacCallum T. Calorie restriction in Biosphere 2: alterations in physiologic, hematologic, hormonal, and biochemical parameters in humans restricted for a 2-year period. J Gerontol: Ser A 2002;57(6): B211–B224.

[18] Walford RL, Harris SB, Gunion MW. Calorically restricted low-fat nutrient-dense diet in Biosphere 2 significantly lowers blood glucose, total leukocyte count, cholesterol, and blood pressure in humans. Proc Natl Acad Sci USA 1992;89(23):11533–7.

[19] Keramati M, Gutkin BS. A reinforcement learning theory for homeostatic regulation. In: Proceedings of the NIPS; 2011. p. 82–90.

[20] Amin M. Security challenges for the electricity infrastructure. Computer 2002;35(4):8–10.

[21] Amin M. NorthAmerica's electricity infrastructure: are we ready for more perfect storms? IEEE Secur Priv Mag 2003;1(5):19–25.

[22] Amin M, Schewe PF. Preventing blackouts. Sci Am 2007;296(5):60–7.

[23] Bagdasaryan A. Systems theoretic techniques for modeling, control, and decision support in complex dynamic systems; 2010. ⟨arXiv:1008.0775⟩.

[24] Branlat M, Woods DD. How do systems manage their adaptive capacity to successfully handle disruptions? A resilience engineering perspective, complex adaptive systems – resilience, robustness, and evolvability: papers from the AAAI Fall Symposium; 2010.

[25] Fiksel J. Designing resilient, sustainable systems. Environ Sci Technol 2003;37(23):5330–9.

[26] Palma-Behnke R, Ortiz L, Reyes D, Jiménez-Estévez G, Garrido N. A social SCADA approach for a renewable based microgrid – the Huatacondo Project. In: Proceedings of the IEEE Power and Energy Society General meeting; 24–29 July 2011. p. 1–7.

[27] Palma-Behnke R, Benavides C, Aranda E, Llanos J, Sáez D. Energy management system for a renewable based microgrid with a demand side management mechanism. In: Proceedings of the IEEE symposium on computational intelligence applications in smartgrid; 2010.

[28] Chen Y-M, Cheng C-S, Wu H-C. Grid-connected hybrid PV/wind power generation system with improved DC bus voltage regulation strategy. In: Proceedings of the IEEE twenty-first annual applied power electronics conference and exposition, APEC'06; 2006.

[29] Lopes JA, Hatziargyriou N, Mutale J, Djapic P, Jenkins N. Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities. Electr Power Syst Res 2007;77(9):1189–203.

[30] Eltawil MA, Zhao Z. Grid-connected photovoltaic power systems: technical and potential problems – a review. Renew Sustain Energy Rev 2010;14 (1):112–29.

[31] Lasseter L, Abbas A, Marnay C, Stevens J, Dagle J, Guttromson R, et al. Integration of distributed energy resources: the CERTS Microgrid Concept California Energy Commission, P500-03 089F; October 2003.

[32] Noroozian R, Gharehpetian G, Abedi M, Mahmoodi M. Grid-tied and stand-alone operation of distributed generation modules aggregated by cascaded boost converters. J Power Electron 2010;10(1):97–105.

[33] Katiraei F, Iravani R, Hatziargyriou N, Dimeas A. Microgrids management. IEEE Power Energy Mag 2008;6(3):54–65.

[34] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids. IEEE Power Energy Mag 2007;5(4):78–94.

[35] Wandhare RG, Agarwal V. A control strategy to reduce the effect of intermittent solar radiation and wind velocity in the hybrid photovoltaic/ wind SCIG system without losing MPPT. In: Proceedings of the 38th IEEE Photovoltaic Specialists Conference (PVSC); 2012. p. 001399–404.

[36] Blaabjerg F, Teodorescu R, Liserre M, Timbus AV. Overview of control and grid synchronization for distributed power generation systems.Industrial Electronics. IEEE Transactions on 2006;53(5):1398–409.

[37] Paramashivan K, Kaundinya D, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power – a review of literature. Renew Sustain Energy Rev 2009;3(8):2041–50.

[38] Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13(9):2263–78.

[39] Arriaga M, Cañizares CA, Kazerani M. Renewable energy alternatives for remote communities in Northern Ontario, Canada. Sustainable Energy. IEEE Transactions on 2013;4(3):661–70.

[40] Tamimi B, Canizares C, Bhattacharya K. System stability impact of large-scale and distributed solar photovoltaic generation: the case of Ontario, Canada. IEEE Trans Sustain Energy 2013;4(3):680–8.
[41] Paudyal S, Cañizares CA, Bhattacharya K. Optimal operation of distribution feeders in smart grids. IEEE Trans Ind Electron 2011;58(10):4495–503.
[42] Pepermans G, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W. Distributed generation: definition, benefits and issues. Energy policy 2005;33(6):787–98.
[43] Bayod-Rújula AA. Future development of the electricity systems with distributed generation. Energy 2009;34(3):377–83.
[44] Driesen J, Belmans R. Distributed generation: challenges and possible solutions. In: Proceedings of the IEEE Power Engineering Society General Meeting; October 2006. 8 p.
[45] Ilic M, Black JW, Prica M. Distributed electric power systems of the future: institutional and technological drivers for near-optimal performance. Electr Power Syst Res 2007;77(9):1160–77.
[46] Jenkins N. Microgrid market, global forecast & analysis (2012–2022) – focus on renewable power generation, solar photo-voltaics, wind micro-turbines, battery, energy storage & control systems, by types, components & technologies. In: The smart grid concept. Smart grids symposium. Glasgow; April 2010. 〈http://www.researchandmarkets.com/research/l9fq5b/microgrid_market〉.
[47] Molderink A, Bakker V, Bosman MGC, Hurink JL, Smit GJM. Management and control of domestic smart grid technology. IEEE Trans Smart Grid 2010;1 (2):109–19.
[48] Sauma E, Jerardino S, Barria C, Marambio R, Brugman A, Mejía J. Electric-systems integration in the Andes community: opportunities and threats. Energy Policy 2011;39(2):936–49.
[49] Del Sol F, Sauma E. Economic impacts of installing solar power plants in northern Chile. Renew Sustain Energy Rev 2013;19:489–98.
[50] Lindén AL, Carlsson-Kanyama A, Eriksson B. Efficient and inefficient aspects of residential energy behaviour: what are the policy instruments for change? Energy policy 2006;34(14):1918–27.
[51] Sovacool BK. The importance of comprehensiveness in renewable electricity and energy-efficiency policy. Energy Policy 2009;37(4):1529–41.
[52] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renew Sustain Energy Rev 2009;13(6):1513–22.
[53] Guerrero MA, Romero E, Barrero F, Milanés MI, González E. Overview of medium scale energy storage systems. In: Proceedings of the 6th international conference–workshop on power quality, alternative energy and distributed systems journal compatibility and power electronics, CPE 2009; 2009.
[54] Cannon WB. Physiological regulation of normal states: some tentative postulates concerning biological homeostatics. In: Pettit A, editor. A Charles Richet: ses amis, ses collègues, ses élèves. Paris: Éditions Médicales; 1926. p. 91.
[55] Cannon WB. Organization for physiological homeostasis. Physiol Rev 1929;9:399–431.
[56] Cannon WB. The wisdom of the body. New York: W.W. Norton & Company, Inc.; 1932.
[57] Cannon WB. Stresses and strains of homeostasis. Am J Med Sci 1935;189 (1):13.
[58] Schwartz MW, Woods SC, Porte D, Seeley RJ, Baskin DG. Central nervous system control of food intake. Nature (London) 2000:661–71.
[59] Schwartz MW, Baskin DG, Kaiyala KJ, Woods SC. Model for the regulation of energy balance and adiposity by the central nervous system. Am J Clin Nutr 1999;69(4):584–96.
[60] Cloutier M, Wellstead P. The control systems structures of energy metabolism. J R Soc Interface 2010;7(45):651–65.
[61] Csete ME, Doyle JC. Reverse engineering of biological complexity. Sci Signal 2002;295(5560):1664.
[62] Peper A. Intermittent adaptation: a mathematical model of drug tolerance, dependence and addiction. Comput Neurosci Drug Addict 2012:19–56.
[63] Peper A. A theory of drug tolerance and dependence I: a conceptual analysis. J Theor Biol 2004;229(4):477–90.
[64] Hall KD. Modeling metabolic adaptations and energy regulation in humans. Annu Rev Nutr 2012;32:35–54.
[65] Hall KD. Predicting metabolic adaptation, body weight change, and energy intake in humans. Am J Physiol – Endocrinol Metab 2010;298(3):E449–66.
[66] Hall KD. Mechanisms of metabolic fuel selection: modeling human metabolism and body-weight change. IEEE Eng Med Biol Mag 2010;29(1):36–41.
[67] Moore-Ede MC. Physiology of the circadian timing system: predictive versus reactive homeostasis. Am J Physiol – Regul Integr Comp Physiol 1986;250(5): R737–R752.
[68] Peiris AN, Sothmann MS, Hennes MI, Lee MB, Wilson CR, Gustafson AB, et al. Relative contribution of obesity and body fat distribution to alterations in glucose insulin homeostasis: predictive values of selected indices in premenopausal women. Am J Clin Nutr 1989;49(5):758–64.
[69] Romero L, Michael L, Dickens MJ, Cyr NE. The reactive scope model – a new model integrating homeostasis, allostasis, and stress. Horm Behav 2009;55 (3):375–89.
[70] Waterhouse J. Homeostatic control mechanisms. Anesth Intensive Care Med 2010;11(7):274–8.
[71] Hyman SE, Malenka RC, Nestler EJ. Neural mechanisms of addiction: the role of reward-related learning and memory. Annu Rev Neurosci 2006;29:565–98.
[72] Davis GW. Homeostatic control of neural activity: from phenomenology to molecular design. Annu Rev Neurosci 2006;29:307–23.
[73] Turrigiano G. Homeostatic signaling: the positive side of negative feedback. Curr Opin Neurobiol 2007;17(3):318–24.
[74] Frank SA. Evolutionary dynamics of redundant regulatory control. J Theor Biol 2008;255(1):64–8.
[75] Leibel RL, Rosenbaum M, Hirsch J. Changes in energy expenditure resulting from altered body weight. N Engl J Med 1995;332(10):621–8.
[76] Prentice AM. Early influences on human energy regulation: thrifty genotypes and thrifty phenotypes. Physiol Behav 2005;86(5):640–5.
[77] Pattaranit R, van den Berg HA. Mathematical models of energy homeostasis. J R Soc Interface 2008;5(27):1119–35.
[78] Shin AC, Zheng H, Berthoud HR. An expanded view of energy homeostasis: neural integration of metabolic, cognitive, and emotional drives to eat. Physiol Behav 2009;97(5):572–80.
[79] Morton GJD, Cummings E, Baskin DG, Barsh GS, Schwartz MW. Central nervous system control of food intake and body weight. Nature 2006;443 (7109):289–95.
[80] Woods SC, Porte D, Bobbioni E, Ionescu E, Sauter JF, Rohner-Jeanrenaud F, et al. Insulin: its relationship to the central nervous system and to the control of food intake and body weight. Am J Clin Nutr 1985;42 (5):1063–71.
[81] Schweppe FC, Tabors RD, Kirtley Jr. JL, Law SR, Levy PF, Outhred H, et al. Homeostatic control of power systems. In: Proceedings of the fourth energy monitoring and control system conference. Norfolk, VA; November 1979.
[82] MIT Energy Laboratory, MIT Homeostatic Control Study Group. New electric utility management and control systems. In: Proceedings of Conference. Boxborough, Massachusetts. MIT Energy Laboratory; May 30–June 1, 1979.
[83] Schweppe FC, Tabors RD, Kirtley Jr. JL, Outhred H, Pickel FH, Cox AJ. Homeostatic utility control. In: Proceedings of the IEEE transactions on power apparatus and systems. May–June 1980; vol. 3, PAS-99. p. 1151–63.
[84] Sterling TL, Williams RD, Kirtley Jr. JL. Control and monitoring system communications for effective energy use. In: Proceedings of the IEEE Power Engineering Society Summer Meeting. Portland, OR; July 1981. paper no. 81 SM 307-8.
[85] Tabors RD. Homeostatic Control: Economic Integration of SolarTechnologies into Electric Power Operations and Planning. In: MITEnergy Laboratory Technical Report. 77 Massachusetts Avenue, E19-307 Cambridge, MA: Massachusetts Institute of Technology; 1981. p. 02139–4307.
[86] Schweppe FC, Tabors RD, Kirtley Jr. JL. Homeostatic control: the utility/customer marketplace for electric power. In: Proceedings of local heat and power generation: a new opportunity for British industry. St. Helier, Jersey, UK: Inderscience Enterprises; 1981. p. 66–88.
[87] Schweppe FC, Tabors RD, Kirtley Jr. JL. Homeostatic control for electric power usage. IEEE Spectrum 1982:44–8.
[88] Constantopoulos P, Schweppe FC, Larson RC. ESTIA: a real-time consumer control scheme for space conditioning usage under spot electricity pricing. Comput Oper Res 1991;18(8):751–6.
[89] Ramchurn S, Rogers PA, Jennings N. Agent-based homeostatic control for green energy in the smart grid. ACM Trans Intell Syst Technol 2011;2(4) (article 35).
[90] Ramchurn S, Vytelingum P, Rogers A, Jennings N. Agent-based control for decentralised demand side management in the smart grid. In: Proceedings of the tenth international conference on Autonomous Agents and Multiagent Systems (AAMAS 2011). Taipei, Taiwan; 02–06 May 2011. p. 5–12.
[91] Vytelingum P, Voice TD, Ramchurn SD, Rogers A, Jennings NR. Agent-based micro-storage management for the smart grid. In: Proceedings of the 9th international conference on autonomous agents and multiagent systems, vol. 1. International Foundation for Autonomous Agents and Multiagent Systems; May 2010. p. 39–46.
[92] Wiener N. Cybernetics: or the control and communication in the animal and the machine, Cambridge, MA, USA: The MIT Press; 1961.
[93] Rammel C, Stagl S, Wilfing H. Managing complex adaptive systems – a co-evolutionary perspective on natural resource management. Ecol Econ 2007;63(1):9–21.
[94] Allen PM. A complex systems approach to learning in adaptive networks. Int J Innov Manag 2001;5(2):149–80.
[95] De Young R. Changing behaviour and making it stick: the conceptualisation and management of conservation behaviour. Environ Behav 1993;25 (4):485–505.
[96] Von Foerster H. Cybernetics of cybernetics (2nd edition). Minneapolis: Future Systems; 1996; 20–45.
[97] Von Foerster H. In: Yovits MC, Cameron S, editors. On self-organising systems and their environments. London: Pergamon Press; 1960. p. 30–50.
[98] Miller JH, Page SE. Complex adaptive systems: an introduction to computational models of social life. Princeton and Oxford: Princeton University Press; 2007.
[99] Sauma E. The impact of transmission constraints on the emissions leakage under cap-and-trade program. Energy Policy 2012;51:164–71.
[100] Sauma E. Valuation of the economic impact of the initial allocation of tradable emission permits in air pollution control. J Energy Eng – ASCE 2011;137(1):11–20.

[101] Sauma E. Inter-temporal planning of transmission expansions in restructured electricity markets. J Energy Eng – ASCE 2009;135(3):73–82.
[102] Sauma E, Oren S. Do generation firms in restructured electricity markets have incentives to support social-welfare-improving transmission investments? Energy Econ 2009;31(5):676–89.
[103] Sauma E, Oren S. Economic criteria for planning transmission investment in restructured electricity markets. IEEE Trans Power Syst 2007;22(4): 1394–405.
[104] Sauma E, Oren S. Proactive planning and valuation of transmission investments in restructured electricity markets. J Regul Econ 2006;30(3):261–90.
[105] Pozo D, Contreras J, Sauma E. If you build it, he will come: anticipative power transmission planning. Energy Econ 2013;36:135–46.
[106] Pozo D, Sauma E, Contreras J. A three-level static MILP model for generation and transmission expansion planning. IEEE Trans Power Syst 2013;28 (1):202–10.
[107] Spees K, Lave LB. Demand response and electricity market efficiency. Electr J 2007;20(3):69–85.
[108] Hamidi V, Li F, Robinson F. The effect of responsive demand in domestic sector on power system operation in the networks with high penetration of renewables. In: IEEE Power and Energy Society General meeting – conversion and delivery of electrical energy in the 21st century; July 2008. p. 1–8.
[109] Palensky P, Dietrich D. Demand side management: demand response, intelligent energy systems, and smart loads. IEEE Trans Ind Inform 2011;7 (3):381–8.